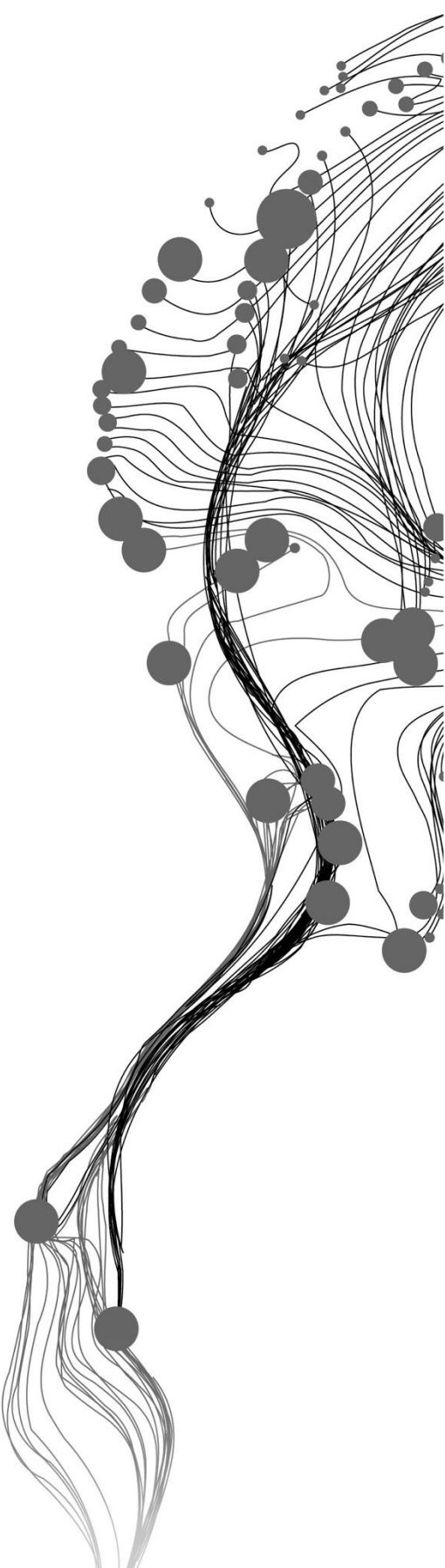


ECOSYSTEM-BASED MEASURES FOR REDUCING SHALLOW LANDSLIDES RISK IN SLOPING TERRAIN

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FEBRUARY, 2016

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ABSTRACT

There is a growing interest in the analysis of the services provided by ecosystems and the need to include them in decision-making in order to achieve sustainable development. Given that vegetation have a substantial role in reducing the probability of a landslide through the root reinforcement and reducing the vulnerability of elements at risk acting as a protective barrier. Little is known about how effective is the implementation of ecosystem-based measures, such as reforestation and grass-based interventions on reducing landslides risk in mountain terrain and their overall performance over time. To address these questions the weight of evidence model seem to be a useful tool to assess landslides susceptibility for two ecosystem based measures scenarios and quantify the overall performance in combination with spatial explicit indicators.

The methodological framework of this research consisted in three step analyses, firstly in the identification of the main terrain factors and landslide prone areas, using an existing landslide susceptibility model. The second step was focused on the evaluation of the effect of ecosystem-based measures on reducing landslides susceptibility, the temporal aspect was considered by linking the land cover changes with a successive type of management. The final step was related to the quantification of the overall performance of the ecosystem-based measures over time, based on a set of criteria and indicators, that can be expressed by landslides risk reduction and other ecosystem services provided including wood provision and carbon storage.

This thesis explores a GIS based approach to assess the effectiveness of ecosystem-based measures over time in reducing shallow landslides susceptibility. It's hoped that this research will help to improve the way ecosystem-based measures are assessed.

Key words: ecosystem-based measures, ecosystem services, landslides, risk reduction.

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1. INTRODUCTION

1.1. Background

According to the Millennium Ecosystem Assessment (MEA, 2005) approximately 60 per cent of all ecosystem services and up to 70 per cent of regulating services are being degraded or used unsustainably over the past 50 years. This assessment was carried out on behalf of the United Nations Environment Programme (UNEP) between 2001 and 2005 to assess the consequences of ecosystem change for human well-being and to establish the scientific basis for actions needed to enhance the conservation and sustainable use of ecosystems and their contributions to human well-being.

It has been demonstrated that ecosystem services (ES) can be used for climate change adaptation and disaster risk reduction, providing natural protection against common natural hazards such as landslides, flooding, avalanches, storm surges, wildfires and drought. Healthy ecosystems also act as buffers, increasing the resilience of natural and human systems to climate change impacts and disasters (Munang, Thiaw, Alverson, Liu, & Han, 2013; MEA, 2005).

To support the awareness that healthy ecosystems can help to reduce disaster risk, Peduzzi (2010) has shown that vegetation cover seems to act as stabiliser in the region of Muzaffarabad and Neelum valley in North Pakistan and India and plays a significant role in decreasing landslides susceptibility triggered by earthquakes. Additionally, the restoration of vegetation coverage in Vietnam's coastline has revealed that planting mangroves for tropical cyclones protection, can reduce the cost of dyke maintenance by over US\$ 7 million per year, while it also provides additional income for local livelihoods (International Federation of Red Cross and Red Crescent Societies, 2002), showing that vegetation cover seems to play an important role in reducing the probability of a landslide stabilizing the slope through the root reinforcement and reducing the vulnerability of elements at risk acting as a protective barrier (Papathoma-Koehle & Glade, 2013).

In most cases vegetation cover and land use are taken in to account in landslides risk management, hazard assessment and hazard zonation in Europe, including France (Papathoma-Koehle & Glade, 2013). In recent years, there has been a growing interest in the analysis of the services provided by ecosystems and the need to include them in decision-making in order to achieve sustainable development (Dominati, Patterson, & Mackay, 2010). However, the ecosystem services of vegetation as far as reducing the physical vulnerability of buildings and infrastructures and provide other local and regional benefits has yet to be well recognized.

The present study aims to facilitate simple methods and obtain solid scientific assessments (Peduzzi, 2010) to show the overall effect of different type of vegetation on different landslide types (for example, debris flows, shallow translational landslides, deep-seated landslides), integrating risk assessment methodologies, Geographic Information System (GIS) tools with ES operational frameworks that provide tested, practical tools to quantify, value and map ES (Martínez-Harms & Balvanera, 2012).

1.2. Problem Statement

Landslides represent a major hazard in the Barcelonnette basin in Southern France, where the combination of factors (e.g. lithology, surface deposits, and land use) creates favourable conditions for the triggering of mass movements (Lopez Saez, 2011). In fact, landslides have been extensively studied in the European Alps. One of these locations, where a large amount of data are available is the Barcelonnette basin (Flageollet, Maquaire, Martin, & Weber, 1999; H. Y. Hussin, 2011; Remaître & Malet, 2010). The basin has experienced since the 17th century extensive clear cutting of forests on slopes due to an increase in cultivation, and later, tourism. This has made the area more susceptible to landslides (Malet, Laigle, Remaître, & Maquaire, 2005).

Since 1860 until 1940, French government through the RTM (French Mountain Terrain Restoration Agency) and the ONF (French Forestry Office) implemented a combination of different kind of watershed and land use management measures and technical defence works to prevent or reduce mountainous hazards or their effects. According to the study of Liébault & Taillefumier (2000) based on a detailed analysis of land use changes and the history of torrent control works done by RTM, most of the reforestation works took place in the period 1863- 1917 (see Figure 1), almost 90% of all the work has been done in 54 years.

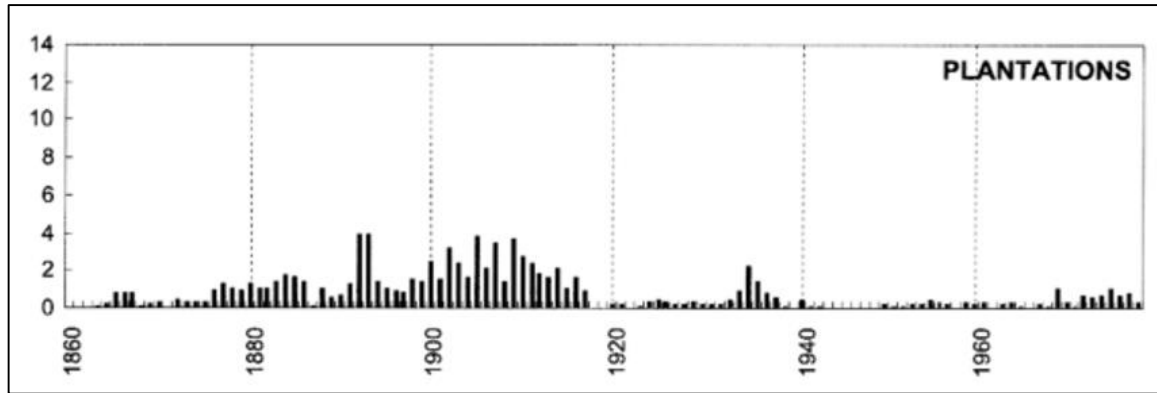


Figure 1: Chronology of the reforestation works done by RTM. The values correspond to the percentages of the total amount of work throughout the period (Liébault & Taillefumier, 2000).

Two phases can be distinguished: a) Initiation works (1863-1887) established by the laws of 1860 and 1864, characterized by the works of the facility of torrent control (dams, sills, and others), as well as by significant grassing operations. This is the stage prior to reforestation, which aims to establish optimal stability conditions to increase the chances of success of plantations and seedlings that truly started in the 1890s. b) Reforestation (1887-1914) phase initiated by law in 1882, most of the work (planting, seeding) was carried out. The main species used to reforest the area were the Austrian Pine (*Pinus nigra subsp. nigricans*) and Scots pine (*Pinus sylvestris*).

The grassing operations consisted in planting herbaceous vegetation especially to provide transitional protection for young plants sensitive to climate assaults and erosion in elevated slopes, where the ground surface is not stable enough for tree species (Demontzey, 1882). Since 1863, ecosystem system based interventions are still being implemented by RTM.

However, the lack of knowledge on the effectiveness of reforestation on reducing landslides risk based on total performance over time, related to grass-based interventions, shows the need of the temporal and spatial analysis of these ecosystem-based measures in the study region and can be valuable for long term strategic landscape level planning. Given that forests and grassland ecosystems have a significant influence on reducing the likelihood of shallow landslide and superficial erosion (Alcántara-Ayala, Esteban-Chávez, & Parrot, 2006; Stokes et al., 2014) this research will focus on this type of landslides. The effectiveness will be defined over time, specifically taking into account the time lapse when the ecosystem-based measures like reforestation and planted grasses starts to be effective on reducing landslides susceptibility.

1.3. Research Objectives

The main objective of this study is to develop a GIS based methodological framework to assess the effectiveness of ecosystem-based measures over time in reducing shallow landslide susceptibility.

To achieve this objective the following specific objectives are defined:

1. To assess shallow landslide prone areas and terrain factors using weights of evidence model.
2. To evaluate the effect of reforestation and planted grasses ecosystem-based measures on reducing landslides susceptibility over time.
3. To quantify the overall performance of different ecosystem-based measures over time.

The following research questions will be addressed:

- What factors determine shallow landslide prone areas? What is the susceptibility of the study area to shallow landslides?
- How long does it take until the ecosystem-based measures starts to have an effect on landslides susceptibility? What is the effect of each reforestation and planted grasses ecosystem-based measures on reducing landslides susceptibility over time?
- Which are the criteria and indicators to measure the effectiveness of the implementation of ecosystem-based measures? What is the overall performance for both ecosystem-based measures over time?

The hypotheses of this research are:

1. Shallow landslides are largely determined by land cover and slope.
2. Planted grass shows faster result on reduction landslides susceptibility.
3. Reforestation measures lead to a higher overall performance than grass-based measures over time.

1.4. Thesis outline

The structure of this thesis follows the steps analysis used to address the main objective and research question. Figure 2 shows the relationship of the chapters and the overall methodological framework.

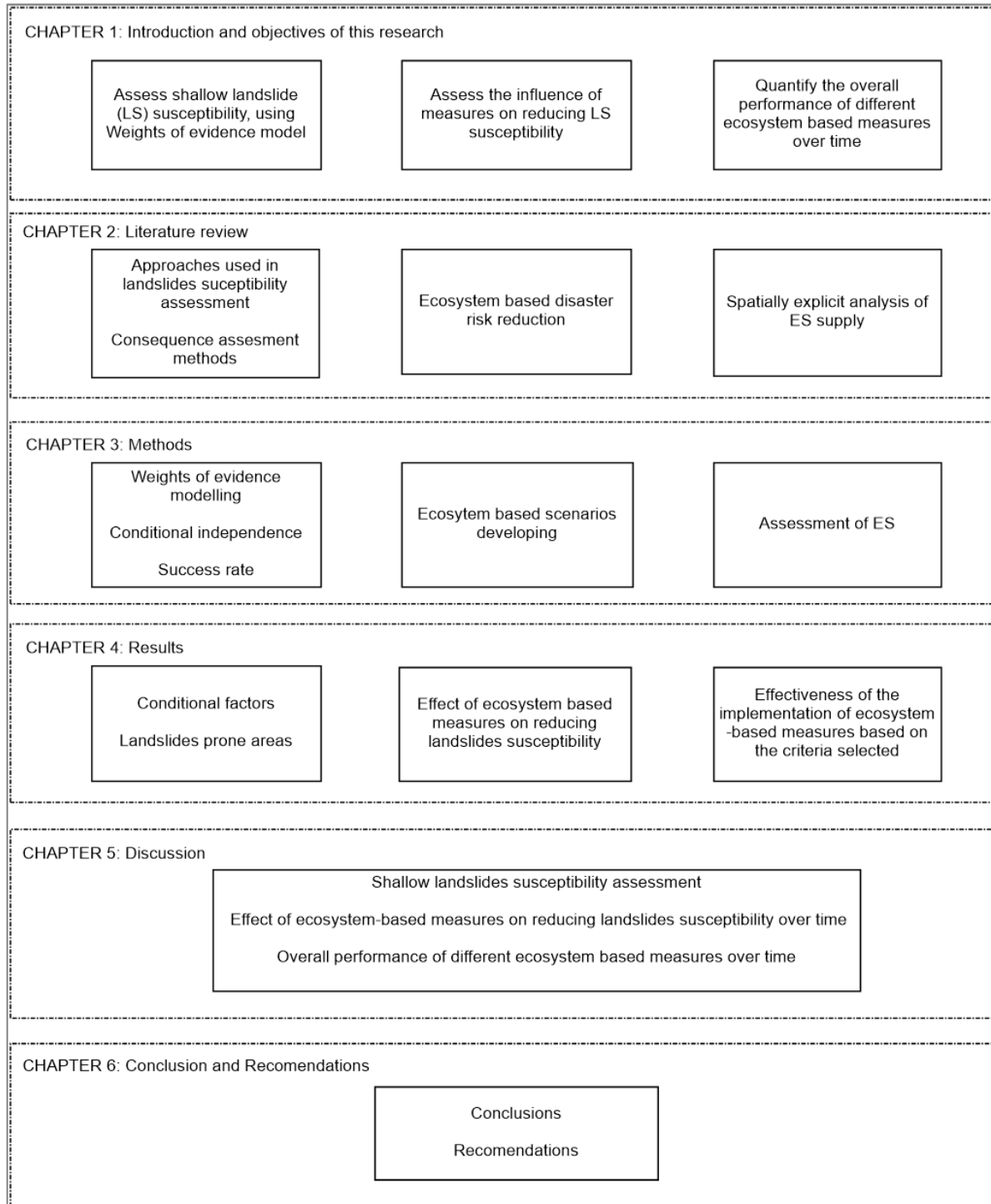


Figure 2: Overall methodological framework in relation with thesis chapters

2. LITERATURE REVIEW

This chapter presents the main concepts used in the methodological framework to assess the effectiveness of ecosystem-based measures over time in reducing shallow landslide susceptibility.

2.1. Landslides susceptibility assessment

The risk management process comprises three main components: risk analysis, risk evaluation and risk treatment (Australian Geomechanics Society, 2000). In order to calculate landslides risk, it's necessary to integrate the behaviour of the hazard (hazard analysis) with the elements at risk and their vulnerability (consequence analysis), usually in the form of the generic hazard/risk equation (Crozier & Glade, 2005). Figure 3 shows all the components involved in landslide risk management and their hierarchical relationships.

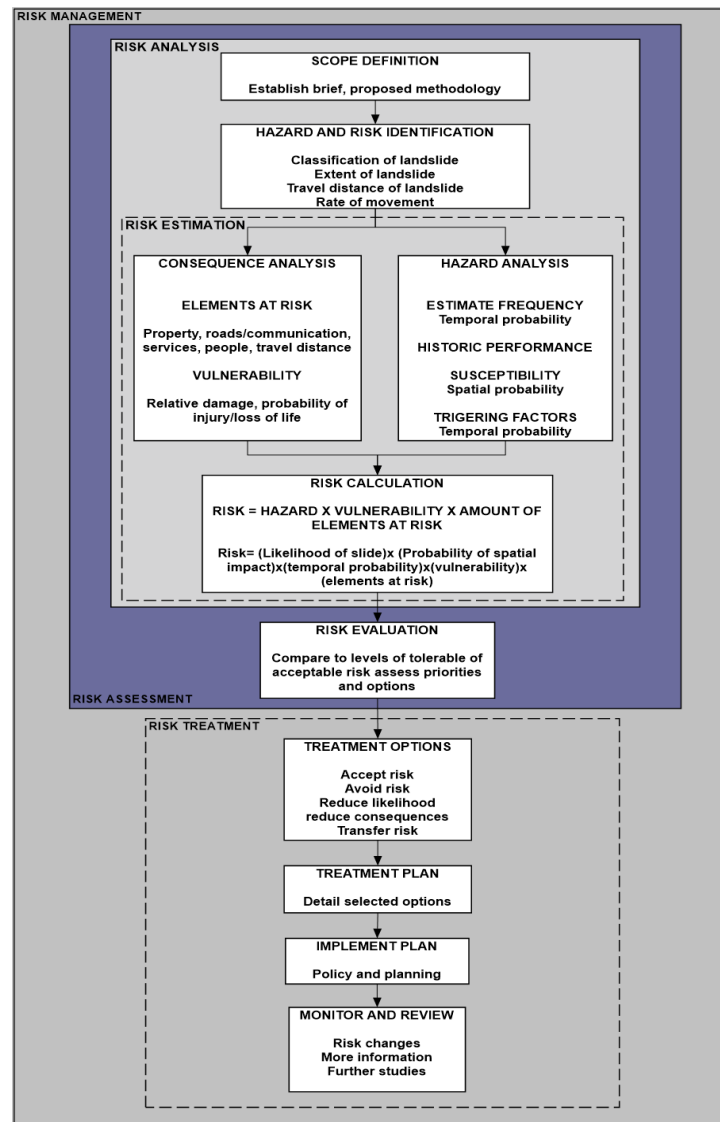


Figure 3: Landslide risk management flowchart, based on Australian Geomechanics Society (2000) and Crozier & Glade (2005).

In this context, the concept of risk combines the likelihood of a landslide event with an assessment of its impact or potential consequence, therefore the selection of a method depends on the objective, geographic scale of analysis, and the amount of data available (Glade, 2002). Puissant et al. (2006) distinguished two analysis scales: a) regional scale, where hazard, consequence and risk are mapped for vast areas at coarse scales (1:50.000 to 1:10.000) with the objective to locate the most sensitive risk areas and to target high-risk locations for detailed risk assessments; b) local scale where hazard, consequence and risk are computed for individual landslides at fine scale (1:5000 to 1:1000), with the objective of quantitatively assess occurrence probabilities and magnitudes of hazardous events. As well as to evaluate the direct and indirect consequences (physical, social, environmental and economic) of the hazard, in order to implement planning procedure or mitigation works. This research focuses in the assessment of the effect or impact of mitigation works like reforestation and grass interventions in a regional scale, in the areas identified as most sensitive in terms of risk.

2.1.1. Approaches used in landslides susceptibility assessment

Landslide susceptibility is a function of the degree of the inherent stability of the slope with the presence and activity of causative factors capable of reducing the excess strength and ultimately triggering movement (Crozier & Glade, 2005). Consequently, landslides susceptibility assessment can be assessed through the spatial probability of occurrence of known landslide in an area under a set of environmental characteristics (Guzzetti, Reichenbach, Cardinali, Galli, & Ardizzone, 2005), where time frame is explicitly not taken into account (Fell et al., 2008).

In this context, Glade & Crozier (2005) identified four groups of factors promoting instability: 1) conditional (pre-disposing factors) static, inherent factors which not only influence the stability of the slope but more over act as catalysts to allow other dynamic destabilizing factors to operate more effectively. For example, slope materials that lose strength more readily than others in the presence of water, or particular orientation of rock structure may enhance the destabilizing effects of undercutting; 2) preparatory dynamic factors that decrease the stability in a slope over time, without initiation movement. Some examples can be, weathering, climate change, deforestation or slope disturbance by human activity. 3) Triggering factors are those factors that initiate movement, like intense rainstorms or rapid snowmelt, seismic shaking and slope undercutting. These factors are usually external imposed on the slope and 4) Sustaining factors are those that determine the behaviour of 'actively unstable' slopes, like duration, rate and form of movement. Some of these are dynamic external factors such as rainfall, others relate to the progress of the landslide movement or the terrain encountered in the landslide path.

This study focuses on landslides susceptibility assessment and slope, geology, land cover type will be consider as conditioning factors, the assessment of magnitude and frequency of occurrence won't be taken into account, landslides susceptibility is used as a proxy variable of the hazard analysis (Malek, Boerboom, & Glade, 2015)

There are two types of approaches that are used to obtain landslide susceptibility maps: heuristic (direct or qualitative) and statistical or probabilistic (indirect). The direct approach is the determination of the degree of susceptibility directly, based on the expert knowledge about the occurrences of landslides and their hypothesized predisposing factors (Y. Thiery, Malet, Sterlacchini, Puissant, & Maquaire, 2007; Van Westen, Rengers, & Soeters, 2003). Expert develops decision rules or assigns weighted values for the classes of

index maps and overlays them to develop a map of hazards (Regmi, Giardino, & Vitek, 2010). In France, the official methodology to assess landslides susceptibility and hazard is based on direct approaches and is explained in the Prevention of Risk Plan (Y. Thiery et al., 2007).

Indirect approaches use statistical conditional analyses or deterministic models to predict landslide prone areas, based on the information obtained from the interrelation between landslides inventories and conditioning factors (Soeters & Van Westen, 1996; Van Westen et al., 2003). The importance of each factor is determined on the basis of observed relationships with landslides (Regmi et al., 2010). In landslides hazard, two different statistical analyses are used: bivariate and multivariate. In bivariate analyses, each factor map is combined with the landslide distribution map and weighting values based on landslide densities are calculated for each parameter class. A multivariate statistical analysis, simultaneously analyses two or more factors using multiple regression or discriminant analysis to determine the presence or absence of landslides (Nguyen & Liu, 2014; Soeters & Van Westen, 1996).

The present study evaluates the susceptibility to landslides using a GIS-based weight of evidence method, which is basically the Bayesian approach in a log-linear form and uses prior (unconditional) probability and posterior (conditional) probability. This method calculates the weight for each causative factor of a landslide based on the presence or absence of landslides within the area. The fundamental assumption of this method is that future landslides will occur under conditions similar to those contributing to previous landslides. It also assumes that causative factors for the mapped landslide remain constant over time. This method is applicable when sufficient data are available to estimate the relative importance of evidential themes via statistical means (Regmi et al., 2010).

Another advantage of using a weight of evidence method, is that the researcher can validate the importance of each independent predictive variable and decide on the final input maps and the results can be applied to areas currently free of landslides but where conditions may exist for landslide susceptibility (Armas, Stroia, & Giurgea, 2013). Furthermore, this bivariate method is a useful tool to make quantitative estimation of the importance of the various factors involved (Van Westen et al., 2003).

2.1.2. Consequence assessment methods

In general, landslides risk assessments include the consequence analysis of the hazard, which is the assessment of the impact or potential impact of the landslide. The selection of the method depends on the geographic scale of analysis and the amount of data required. At macro scale (1:25,000 to 1:100,000) the analysis is based on expert knowledge, where the elements at risk and critical facilities are identified then valued in a qualitative ranking. Meso scales (1:10,000 to 1:125,000) use composite indices, to measure complex, multi-dimensional concepts that cannot be observed or measured directly. And micro scales (1:5,000 to 1:10,000) for site-specific analyses, the consequences are evaluated quantitatively by using vulnerability factors including physical, social, environmental and economic components, using detailed datasets and complex multicriteria models (Puissant et al., 2006).

The method used in this research is index-oriented because of the ability of indices to synthesize a vast amount of diverse information into a simpler, more usable form and localize highly – sensitive areas over large territories (Puissant et al., 2006). Thus, the consequences of the occurrence of a landslide are expressed qualitatively in terms of loss and measured by composite indices (Glade & Crozier, 2005).

Ecosystem-based disaster risk reduction

One of the strategies to address landslide risk mitigation is the possibility of reducing the probability of occurrence of the hazard (Dolidon, Hofer, Jansky, & Sidle, 2009). In contrast to conventional engineering solutions that are usually focused on reducing the vulnerability (refer to Risk equation in Figure 3) ecosystem-based management has the potential to influence the three elements of the risk equation, in terms of regulating the hazard, control exposure of the elements at risk and reduce vulnerability and still provide multiple benefits for human wellbeing (Renaud, Sudmeier-Rieux, & Estrella, 2013). Marisol & Saalismaa (2012) defines ecosystem-based disaster risk reduction as the sustainable management, conservation and restoration of ecosystems to reduce disaster risk, with the aim of achieving sustainable and resilient development.

It has been proved that mountain forests and other vegetation on hillsides (vegetation cover and root structure) play an important role in the protection against erosion and slope stability by binding soil together, preventing landslides (Dolidon et al., 2009) and reducing the likelihood of shallow landslides (Alcántara-Ayala et al., 2006).

Measures such as reforestation schemes to regulate landslide hazard may have additional benefits to society, like employment in forestry, provide forest products, they might also be used for recreational purposes (Phillips, Rey, Marden, & Liébault, 2013). Berger & Rey (2004) recognize the role of forests in protecting against natural hazards in mountainous areas and emphasize that it also depends on position of the forest, type of vegetation, its age and the spatial scale of the hazard. The protection of the forest can be active (when it is located in the hazard departure zone) or passive (when it is located in the departure and stopping zones).

However, there are other factors that contribute to landslides susceptibility such as slope characteristics (Peduzzi, 2010). Additional measures to regulate the hazard can be bio-engineering measures that is a combination of techniques to stabilize and protect slopes against erosion, reduce the probability of planar sliding and improve surface drainage, reducing landslide hazard (Papathoma-Koehle & Glade, 2013), using the whole plants (woody or wet land plants) or their parts as construction materials to secure unstable sites, as bush-mattress, wattle fences, log brush barrier can also have ecological and economic advantages (Georgi & Stathakopoulos, 2016).

In general, forest cover have regularly been used for slope stabilization, in terms of the reduction of vulnerability and exposure of elements at risk, the protection of ecosystems such as forest as a major component of disaster prevention has been implemented in countries such as Austria, France and Switzerland (Berger & Rey, 2004). According the Austrian Forest Act (2002) the role of protective forest can be divided in three categories of protection: site- protection (they protect themselves); from natural hazards (enhance and maintain positive environmental effects such as climate water balance); and protect human settlements and agricultural areas (Papathoma-Koehle & Glade, 2013; Quadt, van der Maaten-Theunissen, & Krumm, 2013). Heterogeneous forest with a mixture of trees of different sizes and ages are generally considered to provide the best protective effect against natural hazards (Dorren, Berger, Imeson, Maier, & Rey, 2004).

Spatially explicit analysis of ES supply

According to Tallis & Polasky (2009) the value of ecosystem services is determined by the location of ecological processes that create the provision of services (supply) and the location of people who derive benefits from the services (demand). Therefore, the quantification and mapping of this ES play an important role in spatial planning and ecosystem-based management. Several methodological approaches to map ES exist, Martínez-Harms & Balvanera (2012) distinguish five, based on the data sources used to quantify and map the ES supply: The first, establishes binary links between land cover and a constant ES value for supply or demand obtained from previous studies at other places and other spatial scales. The second, corresponds to an expert knowledge approach, when experts are asked to rank an environmental variable category based on the knowledge that they have about the potential of these categories to supply an ES. The third methodology relies on well-known relationships between indicators and ES including information from literature. Methodologies of the fourth category extrapolate ES estimates of primary data such as field. The last category covers quantitative regression model approaches, which corresponds to modelling the relationship between field samples of ES and readily measurable environmental variables.

All these approaches involve a set of different models, demanding abundant data, especially when valuating ES in quantitative or monetary terms. As the focus of this research is to quantify the effectiveness of ecosystem-based measures to stakeholders, the first approach was selected, which consists in deriving information on ES directly from the land use/cover map (Maes et al., 2012).

3. METHODS

This chapter describe the methodological framework to assess the effectiveness of ecosystem-based measures over time in reducing shallow landslide susceptibility, three main steps were followed: shallow landslides susceptibility assessment, evaluation of the effect of ecosystem-based measures on reducing landslides susceptibility over time and the quantification of the overall performance of the ecosystem-based measures over time.

3.1. Study area

The study area is in the Barcelonnette basin located in the municipality of Barcelonnette in the department ‘Alpes de Haute Provence’ of France. The altitude ranges from 1,100 m at the outflow of the River Ubaye up to more than 3000 m on the highest summits surrounding the catchment (Figure 4).

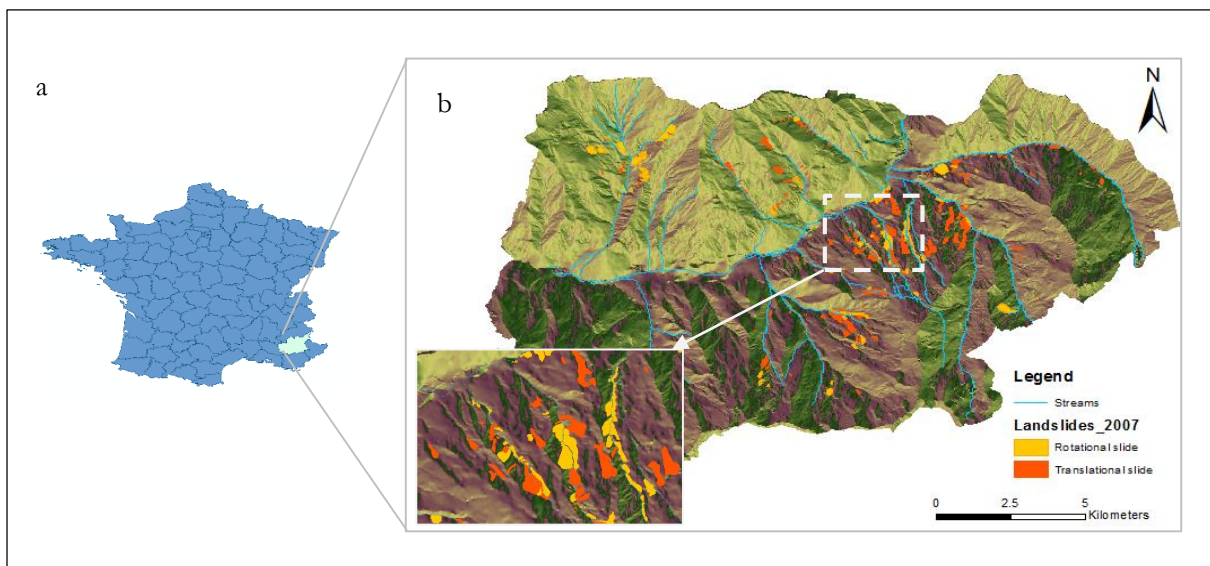


Figure 4: (a) Location of the study area in the department of Alpes-de-Haute-Provence, France (b) Barcelonnette basin (c) Rotational and Translational landslides.

The actual land cover is the result of the presence of several hydro-geomorphological processes in connection with important changes in human activities in the last centuries with high deforestation rate and the introduction of agricultural practices till the eighteenth century. Reforestation and dam building for torrent correction mark the landscape as a result of actions to reduce landslide activities and torrential events largely threatening the human activities.

The area has an important administrative, touristic, commercial function. Most economic activities are situated in the municipalities along the Ubaye River. Touristic activities, especially winter tourism are concentrated on the hillslopes with the ski resorts of Pra-Loup and Sauze/Super – Sauze on the territory of Enchastrayes. Apart from houses, the region contains several administrative buildings, schools, hospitals, shops, hotels, ski infrastructures and industrial parks. The most important lifeline is the main road ensuring the relation with Italy (Puissant, Van Den Eeckhaut, Malet, & Maquaire, 2013).

Due to its predisposing geological structure consisting of limestone and sandstone overlying sensitive clay shales, the hillslopes are affected by severe gullyng, shallow landslides, large deep-seated landslides, debris flows and rock falls (Malet et al., 2005). In this research we will focus on shallow landslides, which includes translational and rotational landslides.

3.2. Overview of the methods

To address the research questions described above, this research followed three step analyses (Figure 5):

- The first step consists in the identification of the main terrain factors and landslide prone areas, using an existing landslide susceptibility model.
- The second step is focused on the evaluation of the effect of ecosystem-based measures on reducing landslides susceptibility over time.
- The third step is related to the quantification of the overall performance of the ecosystem-based measures, based on selected criteria and indicators over time.

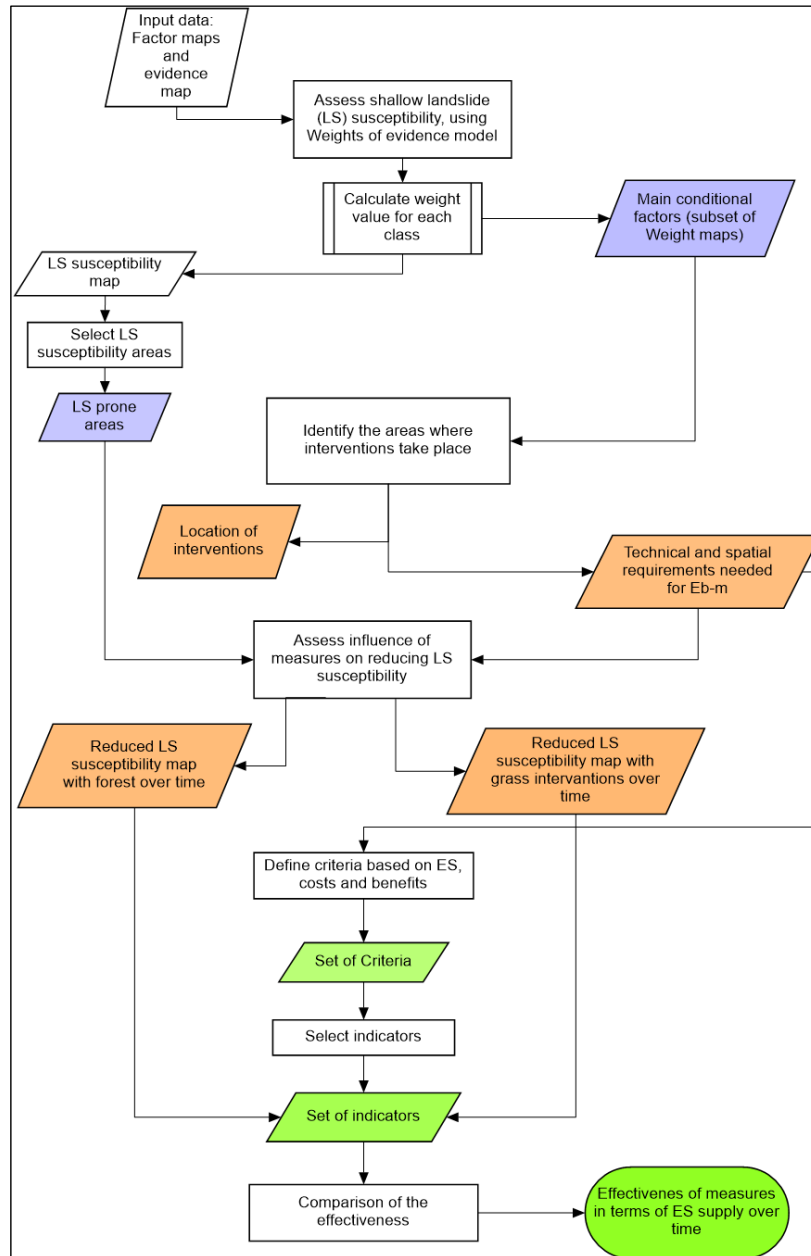


Figure 5: Flow of methods, the coloured boxed indicates the main outcome per research question.

3.3. Assessment of shallow landslide susceptibility

3.3.1. WoE model

The susceptibility assessment is based on the weight of evidence method (WoE). Figure 6 shows the flowchart of the model.

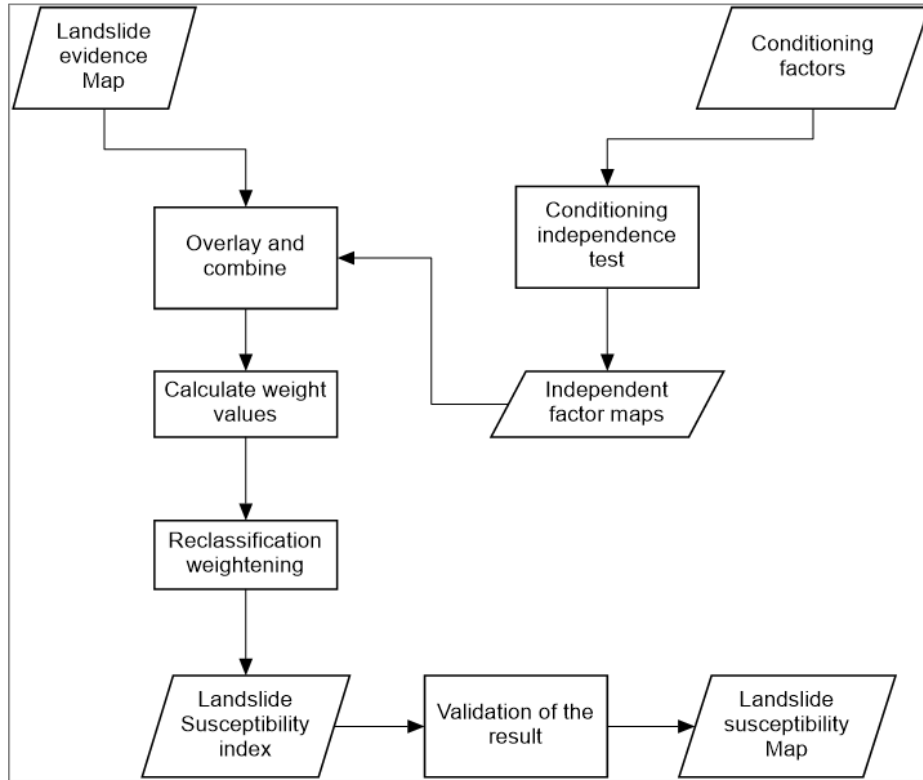


Figure 6: Simplified flowchart of landslide susceptibility model

The calculation of the weights of each conditioning factor was performed using the Weights of evidence model, following the guidelines described in the GIS- based training package on landslides susceptibility mapping of the SafeLand Seventh Framework Programme (2012), which consist in the combination of the conditioning factor and landslides inventory and then the calculation of the landslides densities for each class and the overall landslides density in the entire map (Table 1), using ArcGIS.

Table 1: Weight of modelling equation and variables used.

Equation 1 and 2	$W^+ = \ln \frac{\frac{Npix_1}{Npix_1 + Npix_2}}{\frac{Npix_3}{Npix_3 + Npix_4}}$ $W^- = \ln \frac{\frac{Npix_2}{Npix_1 + Npix_2}}{\frac{Npix_4}{Npix_3 + Npix_4}}$
W+	Positive weight
W -	Negative weight
Npix1	Number of landslides pixel in each factors class
Nslide	Number of total landslide pixel in the whole study area
Nclass	Number of pixels in each factors class
Npix2	Difference between the total number of landslides pixel (Nslide) from landslide pixels in each factors class (Nclass)
Npix3	Difference between the number of pixels in the factors class from the landslide pixels in that class
Npix4	Number of non-landslide pixels in the entire area

The positive and negative weights were calculated using Equation 1 and 2. To quantify the spatial association between a conditioning factor (map class) and the occurrence of landslide the contrast value was calculated

from the difference of these weights for each factor class ($C=W^+ - W^-$) in Microsoft Excel. The final weight per landslide factor was calculated adding all negative weights of the classes of one factor to the positive weight ($W_{map} = W^+ + W_{\min total} - W^-$).

Before combining the adding the Wmap of landslides factors, the statistical independence test of landslides factors among each other was carried out using pair wise comparison method. Then the raster Wmap values of all landslides factors that were conditionally independent, were added to get the landslides susceptibility index map.

3.3.2. Conditional independence

Before combining the weights of different landslide factors, it is important to ascertain that these factors are independent from one another with respect to landslides (Bonham-Carter, 1994). There are three statistical tests for checking the dependency of factors with respect to landslides: a) pairwise comparison; b) principal component analysis and c) logistic regression.

The pairwise and χ^2 tests were used to test the conditional independence (CI) for each conditional factor introduced in the model. For this test all factors maps (raster format) needed to be combined between each other and then combine with the landslides layer. A contingency table calculation was created (see Table 2) for the classes at which pixel of landslides occur. The calculation of χ^2 involved the estimation of the expected number of landslides in each cell under the assumption that area independent. The expected value in a cell was calculated as the product of the marginal pixels divided by the gran total number of pixels.

Table 2: Contingency table of observed frequencies land cover and slope

<i>CF2</i>		<i>SLOPE</i>							
<i>CF1</i>		Flat (0-5°)	Sloping (5-10°)	Strongly sloping (10-20°)	Moderately steep (20-30°)	Steep (30-40°)	Very steep (40-60°)	Near vertical (>60°)	TOTAL
<i>LAND COVER</i>	Coniferous forest	319	1695	7800	5071	1468	318	1	16672
	Coniferous forest mixed	40	579	2486	2070	974	241	9	6399
	Broad leaved forest	440	1193	0	368	81	5	0	2087
	Natural grass	52	384	1051	593	217	34	0	2331
	Arable land	0	0	58	15	1	0	0	74
	Pastures	1	67	396	138	46	3	0	651
	Bare rocks	2	41	410	636	672	189	6	1956
	Black marks	12	5	1138	1921	1478	624	0	5178
	Urban	0	239	8	35	0	0	0	282
	Water	0	223	115	0	0	0	0	338
	Alluvial	0	1	9	1	38	1	0	50
	TOTAL	866	4427	13471	10848	4975	1415	16	36018
$\chi^2 = \sum_{i=1}^{i=4} \frac{(O_i - E_i)^2}{O_i}$									
$d_f = [(number\ of\ class\ for\ Cf1 - 1)(number\ of\ classes\ for\ Cf2 - 1)]$									

The null hypothesis of CI is tested by determining if the measured value exceeds a theoretical value, given the number of degrees of freedom (df) and the level of significance (α). The level of significance was taken as 95% or $\alpha=0.05$.

In general the conditioning factor used for quantitative approaches of landslides susceptibility are: slope, lithology, superficial formation and land cover (Clerici, Perego, Tellini, & Vescovi, 2002). In this case, the choice of the predisposing factors was made according the statistical analysis of the landslide inventory (conditional independence test), their use in previous studies (Flageollet et al., 1999; Y. Thiery et al., 2007) and the availability of data.

3.3.3. Model validation

The predictive power of the resulting weight maps can be tested by analysing their success rate (SR). The SR indicates the percentage of all landslides occurring at the location with the highest values of the landslides susceptibility.

SR is calculated by ordering the pixels of a susceptibility map in a number of classes from high to low values, based on the frequency information from the histogram. After that an overlay is made with the landslide inventory map and the joint frequency is calculated. The SR indicates how much percentage of all landslides occurs in the pixels with the highest values in the different combinations maps.

In statistical approaches, the total area of landslides (Van Westen et al., 2003) or only the triggering area or scarp zones (Thiery et al., 2004) can be used to compute the probabilities of landsliding. However, as the aim of this study is to locate areas prone to failures (Thiery et al., 2007), only the scarp zone of active rotational and translational landslides were introduced in the analysis.

Only a percentage of the scarp zones of active landslides were introduced in the analysis. The sampling strategies and sizes used to prepare the susceptibility model area described in Figure 7.

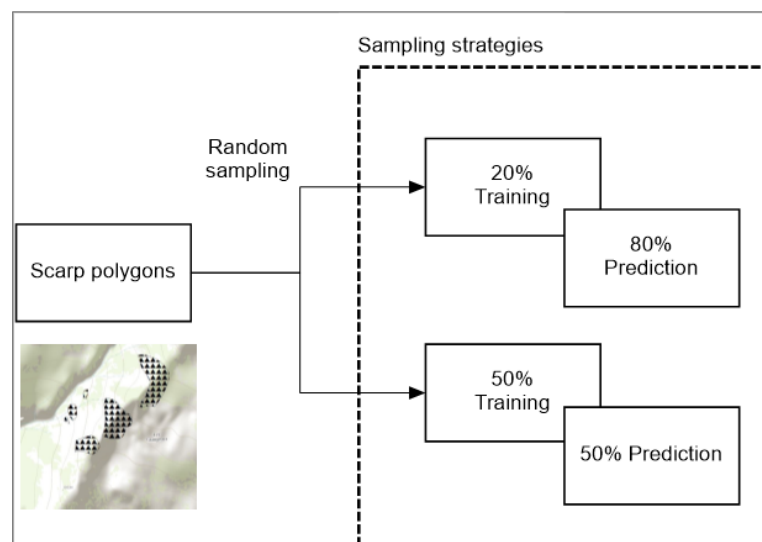


Figure 7: Sampling strategies

For collecting the subsets to train the susceptibility model (training set) and to assess its predictive capability (prediction set) data polygon –based random sampling was used, then converted to raster layer.

The landslides susceptibility procedure followed the sample strategy of Hussin et al. (2015) and the procedure use by Thiery et al. (2004) for the conditional independence test and validation of indirect susceptibility maps.

3.4. Evaluation of the effect of ecosystem-based measures on reducing landslides susceptibility over time

Based on the information provided by the personnel of RTM during the interviews, the measures implemented in the study area for reducing the hazard caused by shallow slides include draining water from the slope (in depth and at the surface, re- profiling of the slopes and the plantation of trees (coniferous trees/grasses(*Ononis fruticosa* L.). Therefore, the type of ecosystem-based solutions that are assessed in this research are forest and grass interventions

Additionally, according to the French official methodology (expert rules) used to define the susceptibility classes, the mitigation works are essential for future human and socio-economic developments of the area in slopes between 20-30 degrees. Therefore, in order to identify the location of ecosystem-based measures and assess their effect on reducing landslides susceptibility, three main criteria were applied: areas that present high susceptibility to landslides, slopes between 20-30 degrees, and areas within a distance of 500 m to elements at risk (EaR). Figure 8 shows the illustrations of the scenarios developed.

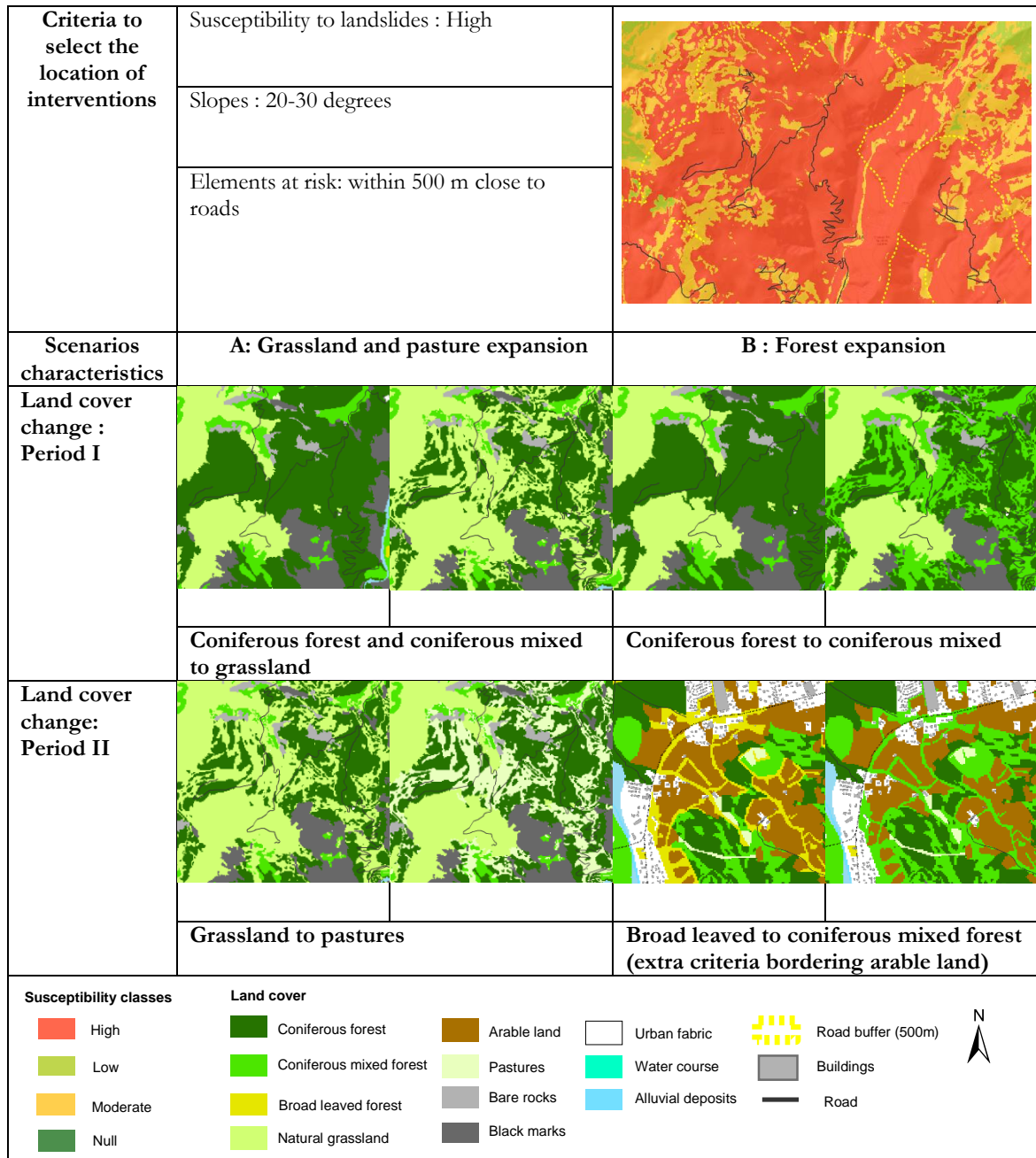


Figure 8: Scenarios characteristics

As this research aims to study the effect of ecosystem-based measures (land cover types) in mountain areas, the goal of this scenarios is mostly descriptive, to show what might happen in terms of landslides susceptibility if the ecosystem-based measures took place. Therefore, the interventions (land cover types) were selected based on the information provided by RTM, resulting in most likely land cover change processes with less probability to present landslides (based on the spatial probability assessment).

To represent the choices of decision makers or other stakeholders towards achieving the effectiveness of ecosystem-based management, the methodological framework includes the time aspect in the successive type of management, implemented in two periods. Considering the land cover of 2008 as the base case, and create two sequential future scenarios to predict how the basin will look after the implementation of ecosystem based measure and assess other potential benefits.

Therefore, two processes of land cover change were developed: grassland expansion (deforestation) and forest expansion. Grassland expansion was defined as a successive land-cover transition from forest to grassland and the pasture. The interventions took place in the coniferous forest and grassland areas to expand pasture areas, assuming that pasture cover will reduce the spatial probability of landslides to occur.

For the forest expansion scenario, the influence of three classes of forest were analysed, in particular Coniferous mixed forest based on their statistical relation with landslides, selecting two possibilities of cover change: coniferous and broad leaved forest with limited change to coniferous mixed forest and the expansion from broad leaved to coniferous mixed forest in areas bordering arable land to protect arable land from the occurrence of landslides.

Both land cover transition scenarios served as future land cover maps when performing the landslides susceptibility assessment and the quantification of ES.

3.5. Quantification of the overall performance of different ecosystem-based measures over time

The overall performance of the measures was evaluated based on: a) spatial explicit ecosystem services assessment: to measure the effects on the supply of ES and b) risk reduction based on the landslide susceptibility and consequence assessment.

A spatial explicit approach was applied, using the changes of the land cover and their effect on the supply of ES, resulting from the simulation of the implemented ecosystem-based and compare the performance with the land cover without interventions (base line). The indicators selected are described in Table 3.

Table 3: Indicators for quantifying and mapping the ES

<i>ES CATEGORIES</i>	<i>ES INDICATOR</i>		<i>DATA SOURCE</i>
Provisioning	Growing stock	(Coniferous forest + Coniferous mixed forest) * 156 m ³ /ha	Growing stock – Commercial Forest available for wood supply in France, year 2005 (Eurostat, 2009).
Regulating	Carbon storage	(Coniferous forest class Ha * 100 Ton/Ha) for Coniferous forest >20 years (Coniferous forest class Ha * 15 Ton/Ha) for Coniferous forest <20 years (Broad leaved class Ha * 100 Ton/Ha) for Broad leaved forest >20 years (Grassland class Ha * 6.75 Ton/ Ha)	Above-ground biomass in forest plantations (Table 4.8) and default biomass stocks present on grassland, after conversion from other land use (Table 6.4). The values are in biomass dry matter Ton/Ha, so carbon storage was estimated by taken a fraction of the biomass (0.5) (IPCC, 2006)
	Reduced risk/impact	(Landslides spatial probability index) * (Potential Damage Index)	Calculated in this research, for the conditions of the study area.

Provisioning services

Raw materials

Forest ecosystems provide the community of Barcelonnette at a local and regional scale with many resources, among which wood is the most important principally from Coniferous trees. The mapping of this service was performed estimating the spatially-explicit volume of timber and fuel wood. The analysis of the growing stock for the two ecosystem-based measure scenarios was done comparing the initial situation and the ability of the new covers (coniferous mixed) to provide wood. Assuming that an increase of forest cover leads to more forest volumes of timber that can potentially use as a resource. The potential timber harvest was calculated using the extent of the new projected forest (Coniferous mixed forest and Coniferous forest) and the value of growing stock taken from the forestry statistics of France.

Regulating services

Carbon storage

For the quantification of the carbon storage, the vegetation (land cover type) was reclassified according to their carbon storage potential in two classes High (coniferous and coniferous mixed forest) and Low vegetation (grassland and pasture) using the values in Table 3, which reflect the temporal aspect in the amount of biomass expected of forest cover. To reduce the complexity of our analysis we did not include carbon storage of below ground biomass.

Landslides risk reduction

The risk reduction was considered as the product of the landslide susceptibility assessment (described in Section 3.4) and the evaluation of the landslide potential consequences. For this latter one, Figure 9 shows the three steps methodology of Potential Damage Index followed (Puissant et al., 2013).

Firstly, three impacts were selected: physical injury (people in their physical integrity), direct structural and functional effect (buildings, infrastructures, land cover and human activities limited in time) and indirect socio-economic effect (extra local consequences diffuse in time).

Secondly, the relative importance of each EaR was calculated assigning the “damage index” values for the attributes of the EaR identified and a “local index” through an expert weighting, (the values used were adapted from Puissant et al. (2013)). Finally, the calculation of the total potential consequence was performed using the linear combination of the exposed elements associated to their respective indices (damage and local index). The values and dataset of the EaR used by Puissant et al. (2013) in Barcelonnette, were adapted to the available dataset of the Safeland project.

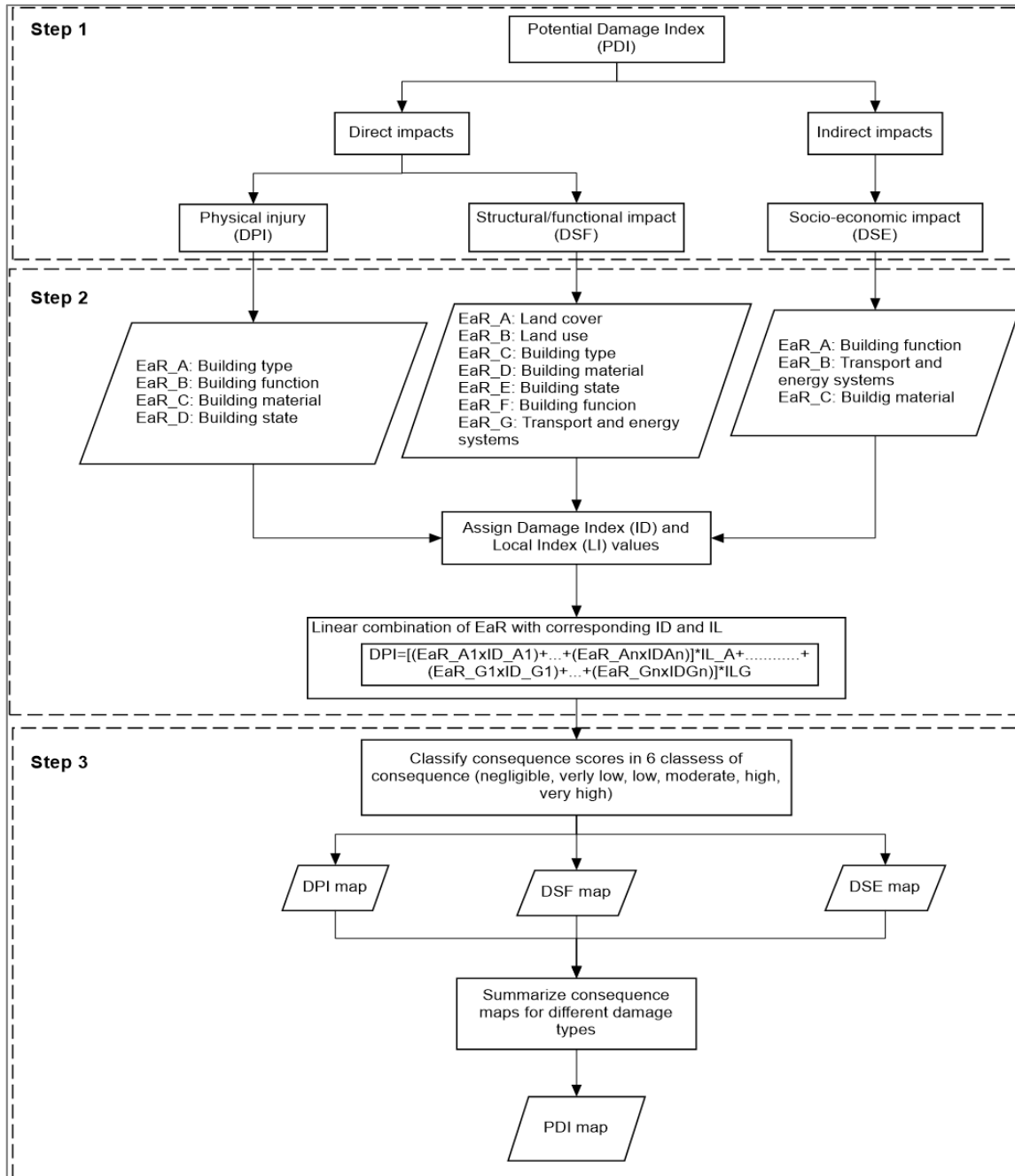


Figure 9: Potential damage index method adapted from (Puissant et al., 2013)

3.5.1. Comparison of the overall performance

In order to guide decision makers toward a judicious choice, in this case the most effective ecosystem-based measure, the overall performance of the ecosystem-based measures was performed comparing the selected indicators with the ones obtained for the base line (no intervention).

3.6. Data review

Shallow landslides have been extensively studied in Barcelonnette basin, therefore the spatial data used was obtained from the GIS training material of the SafeLand FP7 project (2012) that was complemented with the Land cover 2008 data, satellite images and scarp of landslides inventories used in other researches (H. Y. Hussin, 2011), the quality of this data layers will be discussed in Chapter 5.

The input data to calculate landslide susceptibility consist of a map containing information of landslides, which is called an evidence map (landslides inventory) and other data set of ground parameters (conditioning factors) that contains a number of classes that may control the occurrence of the landslide. Table 4 shows the available data used to assess shallow landslide susceptibility and consequence assessment.

Table 4: Available data used

<i>FILE</i>	<i>FILE TYPE</i>	<i>DESCRIPTION</i>
<i>Landslide data</i>		
Landslide_2007 (evidence map)	Polygon	Landslide map with Rotational and Translational landslides
Scarps	Polygon	Scarps or triggering area of landslides
<i>Conditioning factors</i>		
Geotype	Polygon	Surface material map
Land Cover	Raster	Land cover of the year 2008
Slope	Raster	Slope classes used in the hazard analysis, with classes
Streams	Segment	A segment map of the drainage network
<i>Image data</i>		
Barcelonnette_image	Raster image	Presents a high resolution colour image derived from Google Earth. It has been orthorectified and resampled to 1.5 m pixel size
<i>Elements at Risk</i>		
Roads	Polylines	Segment map of roads, principals and secondary roads
Buildings	Polygons	Buildings of the Barcelonnette area with attribute information on building type and uses

The study area was define delineating the Barcelonnette basin using the DEM layer and match with the size of the available layers. The next steps were preparing the landslide conditioning factors and landslides inventory maps and converting them into a raster format with a cell size of 10m with the same geographic projection and extent.

3.6.1. Data collection

The fieldwork had a duration of 6 days, it main purpose was to gather updated data of the study area, related with landslides susceptibility and ecosystem services supply, including the study area exploration and expert consultation. Data collected is described in Table 5.

Table 5: Data collected

<i>DATA</i>	<i>DESCRIPTION</i>	<i>SOURCE</i>
Susceptibility of the area for shallow landslides.	Field conditions (slope and land cover) are processes controlling shallow landslides in the study area	Consult with experts of Strasbourg University French official methodology (expert rules) used to define the susceptibility classes.
Ecosystem-based measures applied in the area	For shallow landslide they usually plant trees or drain the slope. Ecosystem-based measures are implemented to stabilized the slope (two types of species are used, <i>Pinus</i> trees and <i>Ononis</i> - grass)	Interview with the staff in charge of the Restoration in Mountains areas (RTM- Restauration des Terrains en Montagne)
Supply of ecosystem services	Register the evidence of use of ecosystems	Observation and consult with experts

All the available data was checked and modified in order to have it in the same GIS format and coordinate system. This process included the correction of the extent of the projection of the all layers and the generation of new maps that could be useful on the analysis as stream network distance.

4. RESULTS

This chapter presents the results of the application of the methodological framework.

4.1. Shallow landslides susceptibility assessment

The conditional factors used to assess landslides susceptibility in this work were: slope, land cover, geotype and distance to stream.

4.1.1. Description of conditioning factors

In order to assess the spatial probability of shallow landslide in the Barcelonnette basin the aggregation of translational (264) and rotational landslides (124) was required, assuming that both type of landslide have the same controlling factors (Thiery et al., 2004).

Slope

Slope is one of the most important topographic parameter influencing the occurrence of landslides in the study area (Malet et al., 2005). The slope angle map is classified in seven classes in the study area, the classes' strongly sloping, moderately steep and steep cover 77% of the study area, where 85% of the pixel with landslides are located, like is shown in Figure 10.

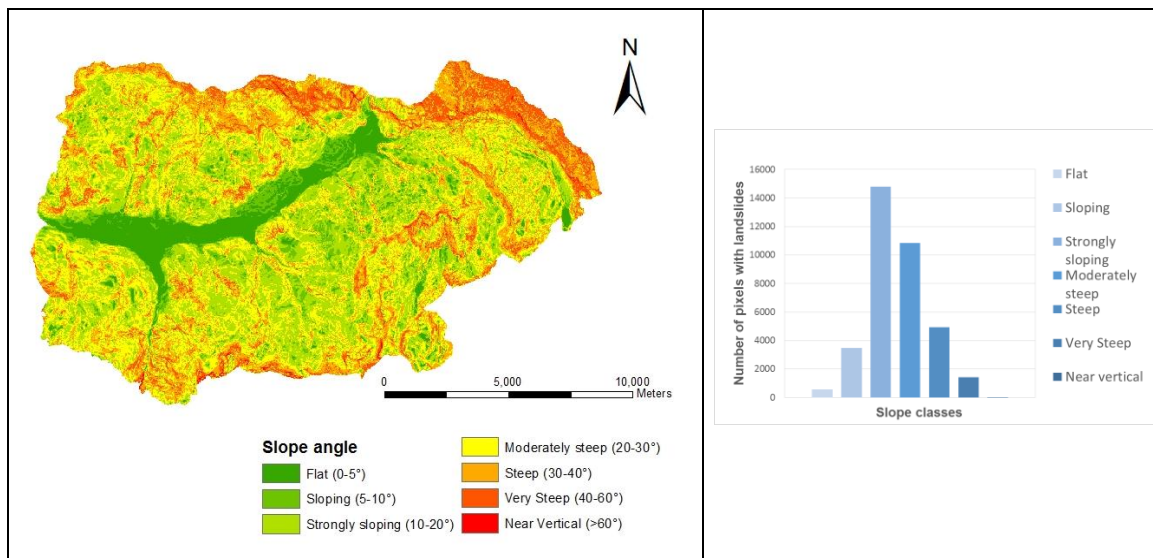


Figure 10: Slope map and frequency graph of landslides in every class.

Geotype

The Barcelonnette basin is located in a complex geological area with 10 geology classes, where Moraine class covers the 50% of the study area and 72% of the pixels with landslides occur in this class, like is shown in Figure 11.

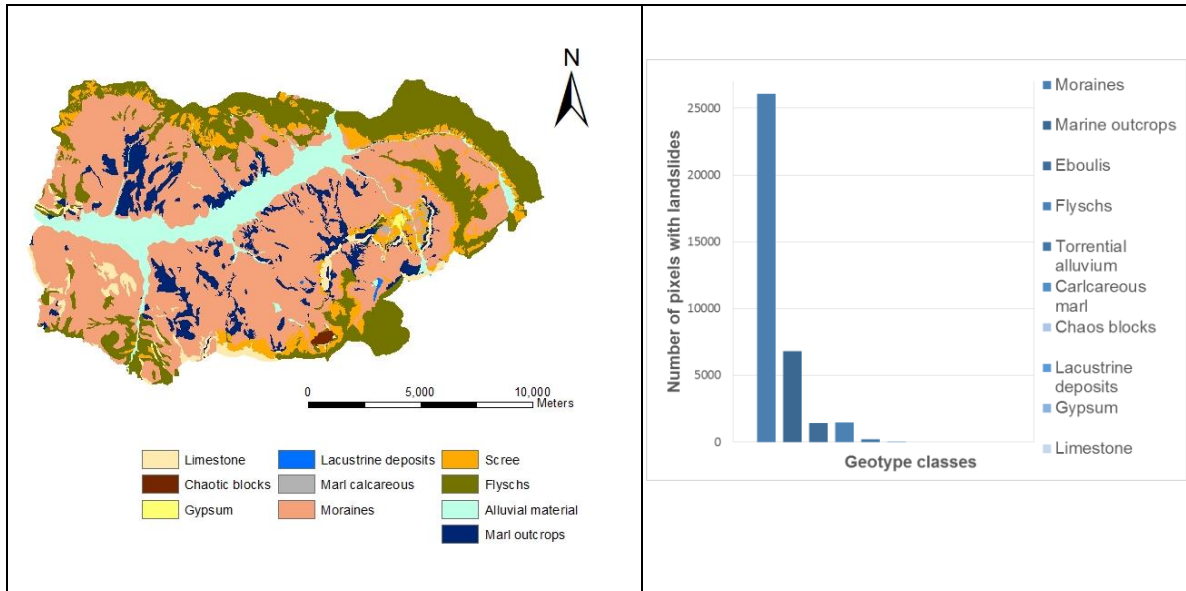


Figure 11: Geotype map and frequency graph of landslides in every class.

Land cover

Land cover is widely considered as an important factor for shallow landslide susceptibility. The vegetation protects slopes against soil erosion, surface runoff and shallow landslide. Slopes where the vegetation is dense and deeply rooted tend to be more stable than those where vegetation it is short or absent (Papathoma-Koehle & Glade, 2013). The French Alps is characterized by geological marl formations this type of geology classified as “black marks” in this map (Figure 12) is very susceptible to erosion and slope instability like is shown in the frequency of landslides in the Barcelonnette basin.

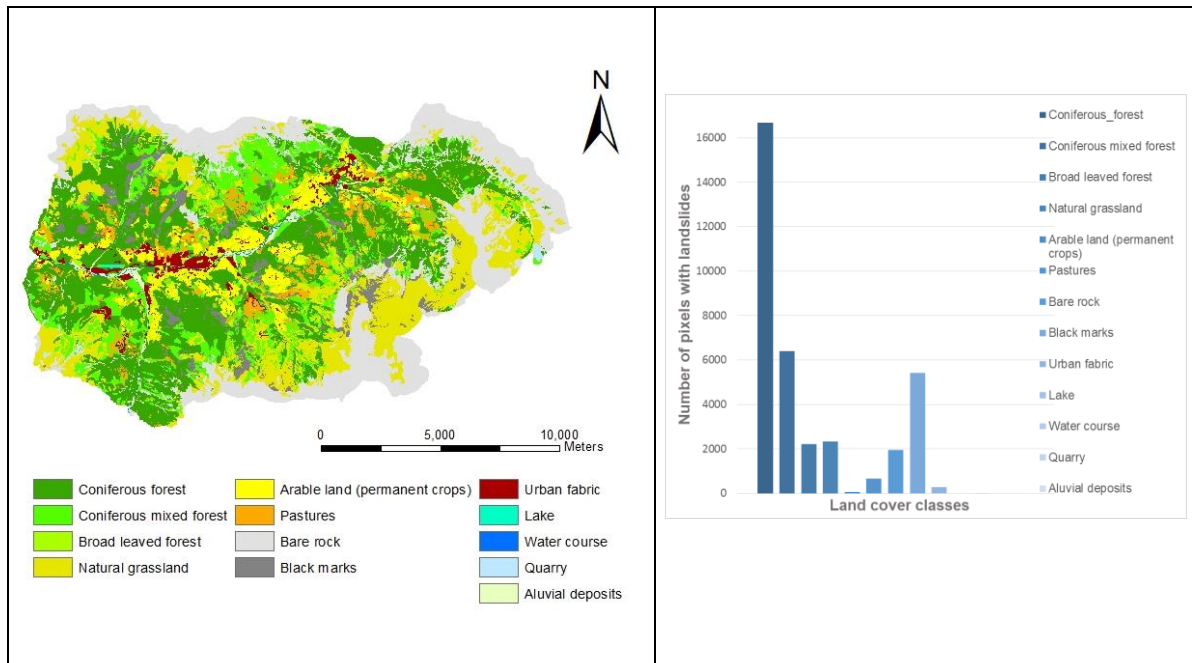


Figure 12: Land cover map and frequency graph of landslides in every class.

Streams

As part of the susceptibility analysis the variable hydrology was used to know the maximum distance of influence of streams, to do this a buffer zone was created every 100 m then it was combined with the landslides inventory to obtain the frequency curve by relating the occurrence of landslides and the distances from each buffer zone (Figure 13), where 87 percent of the pixels with landslides are within 500m from streams.

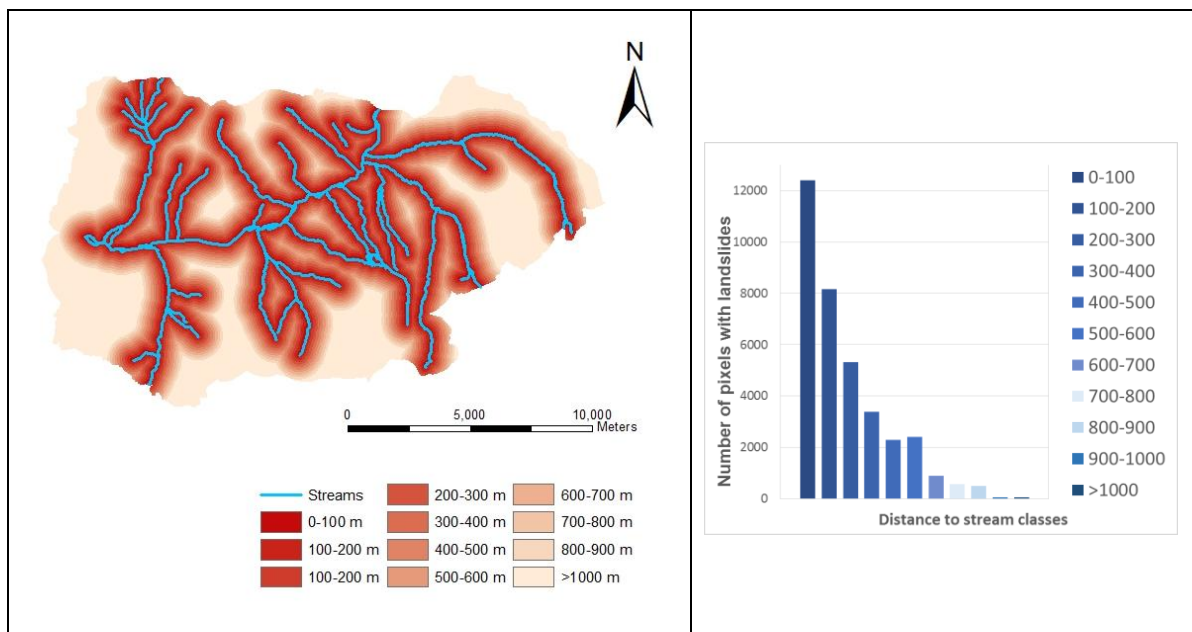


Figure 13: Distance to streams and frequency graph of landslides in every class.

4.1.2. Landslides prone areas

Test for conditional independence

The χ^2 values for testing the conditional independence between classes of conditioning factors were calculated at the 95% significance confidence level. If the calculated χ^2 value between classes of the factors is below the theoretical χ^2 then the pair is independent and they can be used together to map the landslide susceptibility, otherwise the pairs are dependent factors need to be rejected. The values of χ^2 between all possible pairs of the conditional factors are in Table 6.

Table 6: Calculated chi-squared values (χ^2) for testing the independence between all factors.

<i>Factors</i>	<i>Slope</i>	<i>Geotype</i>	<i>Distance to Streams</i>
<i>Land cover</i>	0	0	0
<i>Slope</i>		0	6.89E-91
<i>Geotype</i>			0

Weights of evidence modelling

The spatial relationship between landslide occurrence and the chosen factors have been evaluated using weights of evidence method, Table 7 shows the positive and negative weights and contrast values for all classes of the factors. **W+** indicates presence of the factor in the landslide, therefore the magnitude of the classes “coniferous forest”, “broad leaved forest”, “black marks” is an indication of the positive correlation between presence of the land cover factor and landslides. A **W-** indicates an absence of the causative factor, and the magnitude indicates negative correlation.

Table 7: Weights calculated for classes of conditioning factors.

<i>Factor</i>	<i>Class</i>	<i>Landslides pixels</i>	<i>Pixels in the class</i>	<i>W+</i>	<i>W-</i>	<i>C</i>	<i>Wmap</i>
LAND COVER	Coniferous forest	1151	662688	0.4934	-0.322	0.816	0.707
	Coniferous mixed forest	320	272850	0.1002	-0.015	0.115	0.006
	Broad leaved forest	88	41616	0.6906	-0.019	0.710	0.601
	Natural grassland	220	372783	-0.5872	0.087	-0.674	-0.783
	Arable land /permanent crops	0	128081	0	0.060	-0.060	-0.169
	Pastures	22	105949	-1.6321	0.040	-1.672	-1.781
	Bare rock	175	439224	-0.9802	0.145	-1.126	-1.235
	Black marks	352	95191	1.2511	-0.120	1.371	1.261
	Urban fabric	0	49525	0	0.023	-0.023	-0.132
	Lake	0	1118	0	0.001	-0.001	-0.110
	Water course	1	5359	-1.7390	0.002	-1.741	-1.850
	Quarry	0	2854	0	0.001	-0.001	-0.111
	Alluvial deposits	0	17639	0	0.008	-0.008	-0.117
SLOPE	Flat (0-5 degrees)	26	163390	-1.8983	0.066	-1.964	-2.039

	Sloping (5-10 degrees)	185	161293	0.0779	-0.006	0.084	0.010
	Strongly sloping (10-20 degrees)	917	611806	0.3458	-0.174	0.520	0.445
	Moderately steep (20-30 degrees)	851	629818	0.2420	-0.117	0.359	0.284
	Steep (30-40 degrees)	247	439088	-0.6351	0.111	-0.746	-0.821
	Very Steep (40-60 degrees)	103	183987	-0.6400	0.042	-0.682	-0.757
	Near vertical (more than 60 degrees)	0	5831	0	0.003	-0.003	-0.077
GEOTYPE	Limestone	0	63418	0	0.029	-0.029	-0.226
	Chaotic blocks	0	4878	0	0.002	-0.002	-0.199
	Gypsum	0	3178	0	0.001	-0.001	-0.198
	Lacustrine deposits	0	1764	0	0.001	-0.001	-0.197
	Marl calcareous	0	4313	0	0.002	-0.002	-0.198
	Moraines	1511	1118912	0.2414	-0.334	0.575	0.379
	Eboulis	61	151911	-0.9724	0.045	-1.018	-1.214
	Flyschs	168	475569	-1.1006	0.170	-1.270	-1.467
	Alluvial material	12	200367	-2.8756	0.091	-2.966	-3.163
	Marl outcrops	577	170565	1.1617	-0.204	1.366	1.169
DISTANCE TO STREAMS	0-100 m	575	276160	0.6751	-0.149	0.824	0.797
	100-200 m	481	243149	0.6238	-0.114	0.738	0.710
	200-300 m	427	219324	0.6078	-0.097	0.705	0.677
	300-400 m	337	193235	0.4975	-0.064	0.562	0.534
	400-500 m	118	172280	-0.4381	0.030	-0.468	-0.496
	500-600 m	162	152564	0.0007	0.000	0.001	-0.027
	600-700 m	114	127636	-0.1725	0.010	-0.182	-0.210
	700-800 m	63	105566	-0.5760	0.022	-0.598	-0.626
	800-900 m	45	92722	-0.7828	0.024	-0.807	-0.834
	900-1000 m	3	81650	-3.3642	0.037	-3.401	-3.429
	>1000 m	4	530720	-4.9483	0.275	-5.224	-5.251

The magnitude of the contrast reflects the overall spatial association between the causative factor and landslides. If contrast is positive, the factor is favorable for landslides to occur, and if it is negative, it is unfavorable. If contrast is close to zero, this indicates that the factor shows a small relation to the landslides. The values in grey shows that the land cover, slope and geotype play a main role in translational and rotational landslides in the study area, especially the “coniferous forest” and “broad leaved forest” cover, slopes between “10-30°” and “marine outcrops” classes.

Table 8: Conditioning factors and their relation with the landslide susceptibility classes

<i>Conditional factors</i>	<i>Classes</i>	<i>Conditioning factor maps classes within landslide susceptibility classes in percentage</i>			
		High	Moderate	Low	Null
Slope	Flat	0.01	1.26	0.29	5.89
	Sloping	3.13	2.85	1.26	0.10
	Strongly Sloping	21.04	6.55	0.20	0.10
	Moderately steep	14.71	13.85	0.07	0.07
	Steep	4.79	7.55	7.56	0.09
	Very steep	1.09	2.74	4.50	0.03
	Near vertical	0.01	0.25	0	0
Geology	Limestone	0.67	2.22	0	0
	Chaos blocs	0.01	0.21	0	0
	Gypsum	0.07	0.07	0	0
	Lacustrine deposits	0	0.03	0.05	0
	Marl calcareous	0.04	0.16	0	0
	Moraines	36.53	14.33	0.13	0
	Scree	0.09	4.79	2.01	0.03
	Flyschs	0.12	11.35	10.04	0.13
	Torrential alluvium	7.24	1.36	1.65	6.12
	Marl outcrops	0.67	0.53	0	0
Land cover	Coniferous forest	21.87	6.96	0.07	1.29
	Coniferous mixed forest	7.53	4.28	0.14	0.49
	Broad leaved forest	1.15	0.38	0.02	0.35
	Natural grass	6.35	9.28	1.26	0.1
	Arable land	3.12	0.50	0.83	1.39
	Pastures	0	4.40	0.15	0.29
	Bare rocks	0.11	8.61	11.05	0.23
	Black marls	4.07	0.26	0	0
	Urban area	0.55	0.23	0.20	1.28
	Water	0	0	0	0.05
	Alluvial	0	0	0	0.24
	Quarry	0.01	0.02	0.09	0.01
	Lake	0.02	0.01	0.08	0.57

The values represent the percentage of the conditional factor class area in the final landslides susceptibility map.

Validation and model selection

From the combination of the conditional factors, four models were obtained, like is shown in Figure 14.

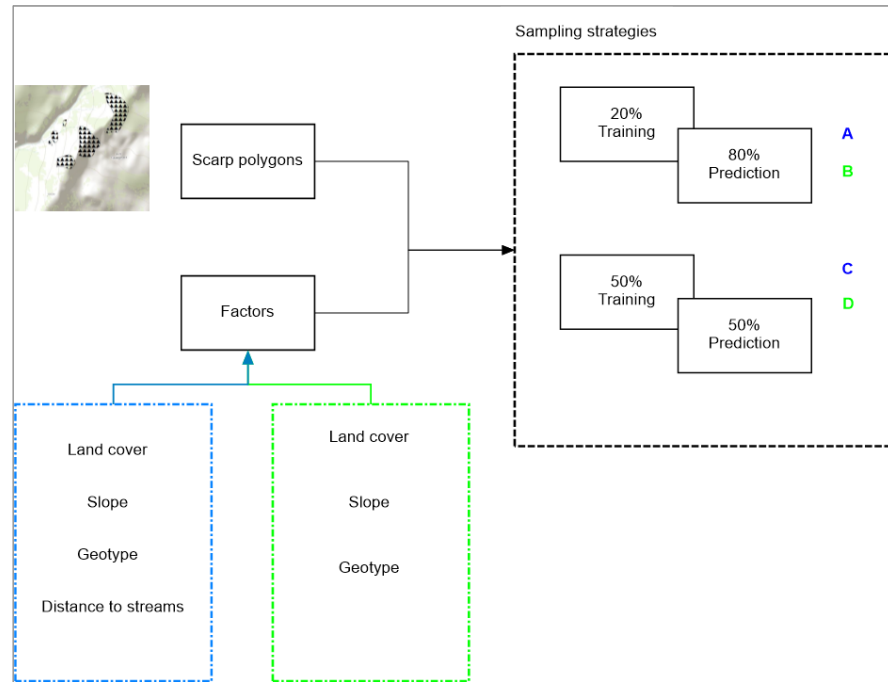


Figure 14: Models developed

The three variables used in the model and their relation with the landslides susceptibility map are represented in Table 7, concluding that in this research the areas with high landslide susceptibility are located in slopes from 10 to 30°, moraines type and in the coniferous forest cover.

The resultant landslide index calculated for 4 models was validated by comparing each with the landslide validation set and calculating the success rate curve of the landslide susceptibility map, which show that 90 % of all new landslides are located in 20% of the map with the highest prediction score (Figure 15).

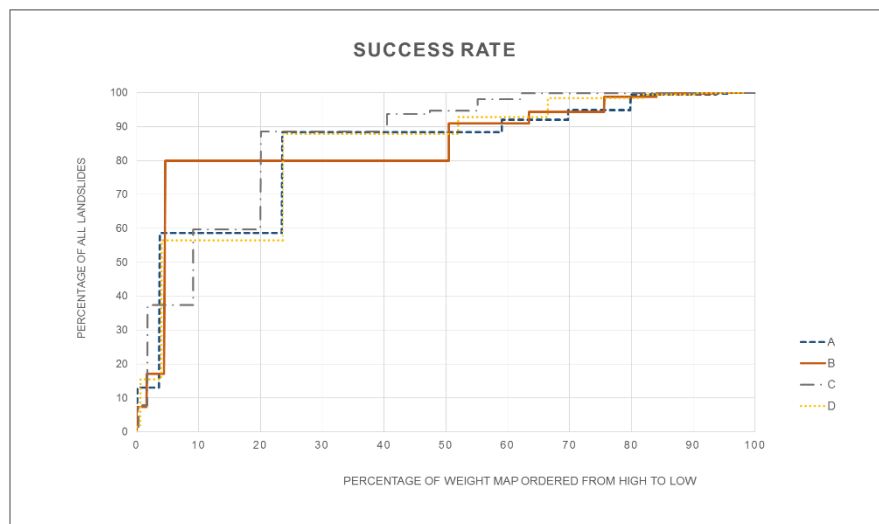


Figure 15: Success rate curve

The area under the curve (AUC) was estimated from the rate curves, this method constitutes one of the most commonly used accuracy statistics for the prediction models in natural hazard assessments (Beguería, 2006). According to AUC values shown in Table 7, model C has the highest prediction accuracy. However there is only a 2% difference with model B, which considers only 3 conditioning factors. In the context of the methodological framework, the selection of the optimal model is based on the model that contains sufficient complexity to explain the landslides phenomena, but no more (Wainwright & Mulligan, 2004). Therefore, model B was chosen as more accurate than others to prepare the final landslides susceptibility map.

Table 9: AUC values

<i>MODEL</i>	<i>FACTORS</i>	<i>TEST TRAINING SAMPLE RATIO</i>	<i>AUC</i>
A	Land cover, Slope, Geotype, Distance to streams	20/80	8285
B	Land cover, Slope, Geotype	20/80	8456
C	Land cover, Slope, Geotype, Distance to streams	50/50	8605
D	Land cover, Slope, Geotype	50/50	8131

Final landslides susceptibility map

The landslides susceptibility map was generated using the Wmap values of model B. Figure 16 presents the landslides susceptibility map where 45 % of the area corresponds to a high susceptibility class, 35% moderate, 14% low and 6 % null. The susceptibility classes breaks were selected based on the steps of the success rate that show the agreement with the landslide inventory map.

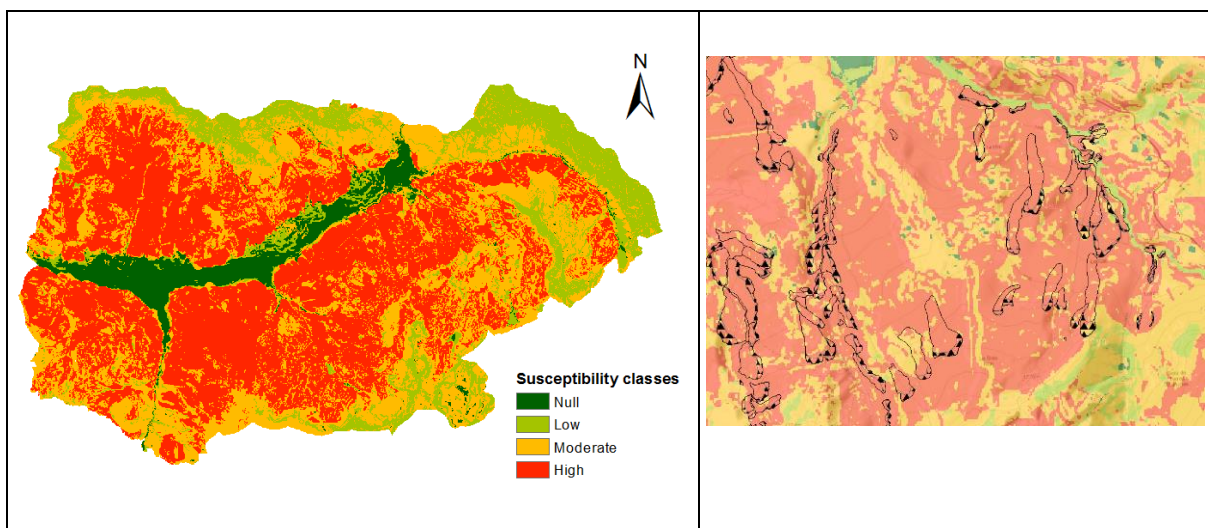


Figure 16: Landslides susceptibility map and the overlay with scarp and cumulative areas of the translational and rotational landslide in the high susceptibility areas.

4.2. Evaluation of the effect of ecosystem-based measures on reducing landslides susceptibility over time

The scenario of maximizing grass (scenario A) resulted in 21 km² of deforestation comparing the areas of forest (Coniferous and Coniferous mixed forest) before and after the implementation of the ecosystem-based measure shown in Table 10, whereas the management that introduce Coniferous mixed forest as a strategy of reforestation resulted in an increase of 70% (19km²) of the mixed forest in comparison to the base line.

Table 10: Comparison of the extent of the pastures and mixed forest classes in the scenarios developed

<i>SCENARIO</i>	<i>AREA (sqkm)</i>			
	Grassland	Pasture	Coniferous Forest	Coniferous mixed forest
Base line: No intervention	37	11	66	27
A: Grassland and pasture expansion (final period)	37	32	51	21
B: Mixed forest expansion (final period)	37	11	66	46

The changes in the mixed forest cover seem insignificant in spatial terms. However, it is important to underline that most of the changes in the forest are in the proximity of the arable land, which aim to have a protection effect in landslides susceptibility.

Additionally, all these changes in the land cover layers had an effect in the landslides susceptibility of the area. Figure 17 presents an illustration of the spatial changes in the susceptibility classes. For scenario A the changes were located mainly in the high and moderate classes and for scenario B in the high, moderate and low classes.

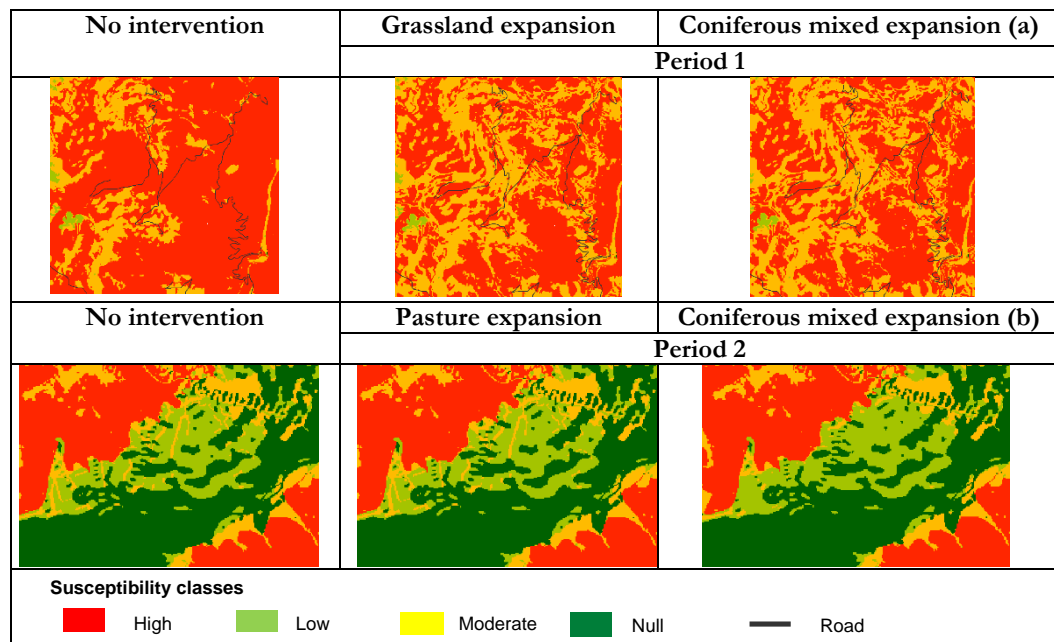


Figure 17: Effect of ecosystem-based measures in landslides susceptibility

For the first period, in Figure 18 the grass interventions (scenario A) have a decrease of 19% of the areas with high landslides susceptibility, and scenario B doesn't show any effect in terms of landslides susceptibility.

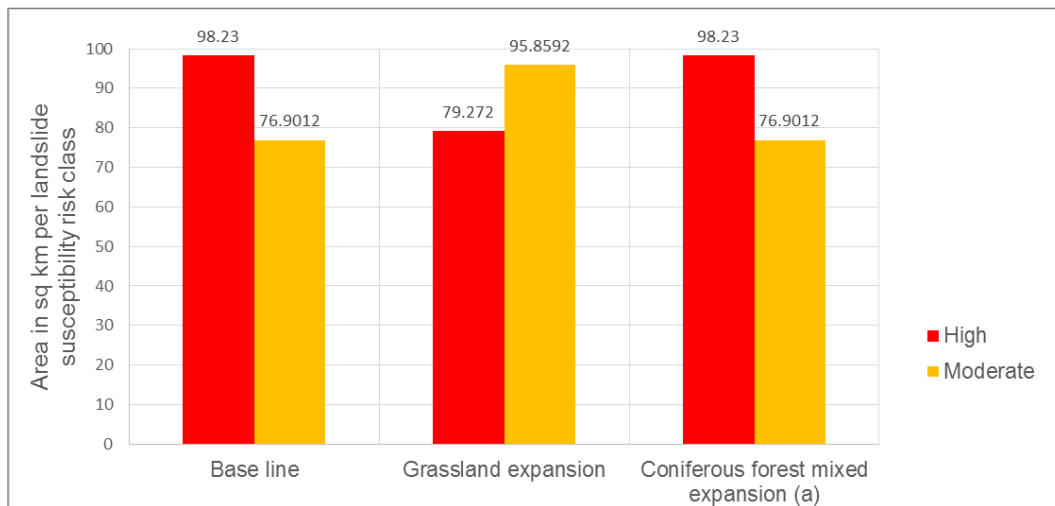


Figure 18: Comparison of the effect of ecosystem-based measures in landslides susceptibility - Period 1

During the second period is when the most important changes are observed (Figure 19), principally for the pasture expansion, where 22% of the high susceptibility area becomes moderate. And the areas where forest ecosystem-based measures have been located show a decrease of 2% in the high, moderate and low susceptibility classes.

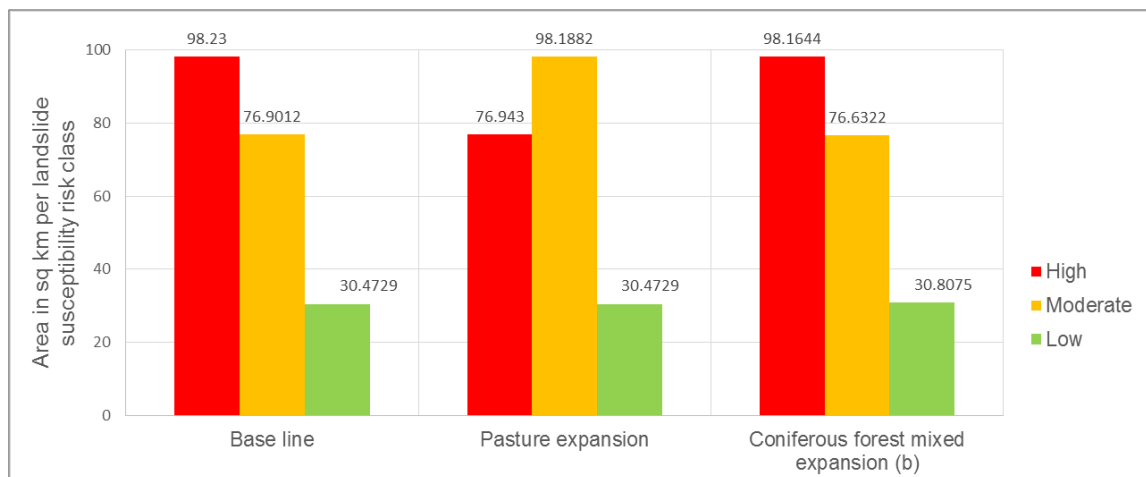


Figure 19: Comparison of the effect of ecosystem-based measures in landslides susceptibility - Period 2

The changes in scenario B are located in the proximity of the arable land, where the landslides susceptibility changes from moderate to low, to analyse this results is important to consider that the area projected to change (Broad leaved forest adjacent to arable land) in this scenario was only 1.8 km².

4.3. Quantification of the service supply of ecosystem-based measures

The mapping and quantification of the service supply, was performed on the land cover layers of the ecosystem-based measure scenarios. The four indicators that were used to quantify the overall effectiveness of the ecosystem-based measures are listed in Table 3.

4.3.1. Effectiveness of the implementation of ecosystem-based measures based on the criteria selected

Provision of raw material

The changes in the supply of ecosystem service are spatially explicit and can be also described in quantitative terms, like is shown in Figure 20, where the most substantial increase (16.5%) of wood provision happens during the first period of scenario B and later in the second period an increase of only 3% of wood for the area, in the areas surrounding the arable land.

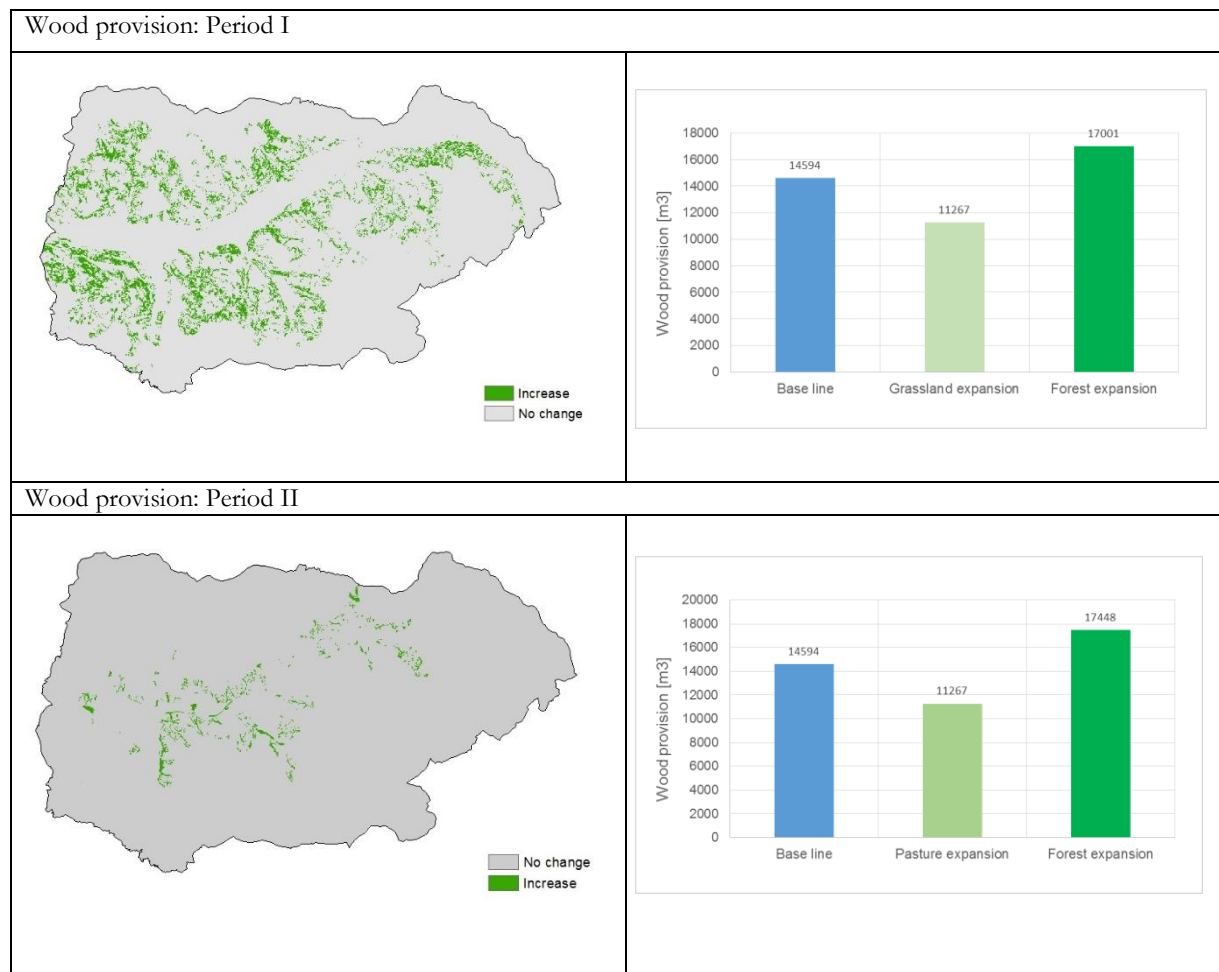


Figure 20: Quantification on the supply of raw material in the study area.

The changes simulated in the land cover extent by the implementation of the ecosystem-based measure can provide favourable effects in the provision of raw material (timber and fuelwood). The maps in Figure 20 present the increase of forest cover in scenario B that can provide approximately 20% more wood for the

area. The opposite happens for the scenario A, which is the conversion from forest to grassland and pasture, in this case, the implementation of the measure result in a negative effect in the provision of raw material.

Carbon storage

In terms of carbon storage, considering that the changes generated by the two ecosystem-based scenario involved the change of cover from Coniferous forest to grassland and Coniferous forest to Coniferous mixed forest, the expected and reasonable result is a reduction in the total carbon storage. However, if we only compare the carbon storage of the grassland during the first period (Figure 21 –Carbon storage in grassland map – Scenario A), there is an increase of 44% in comparison to the initial for scenario A.

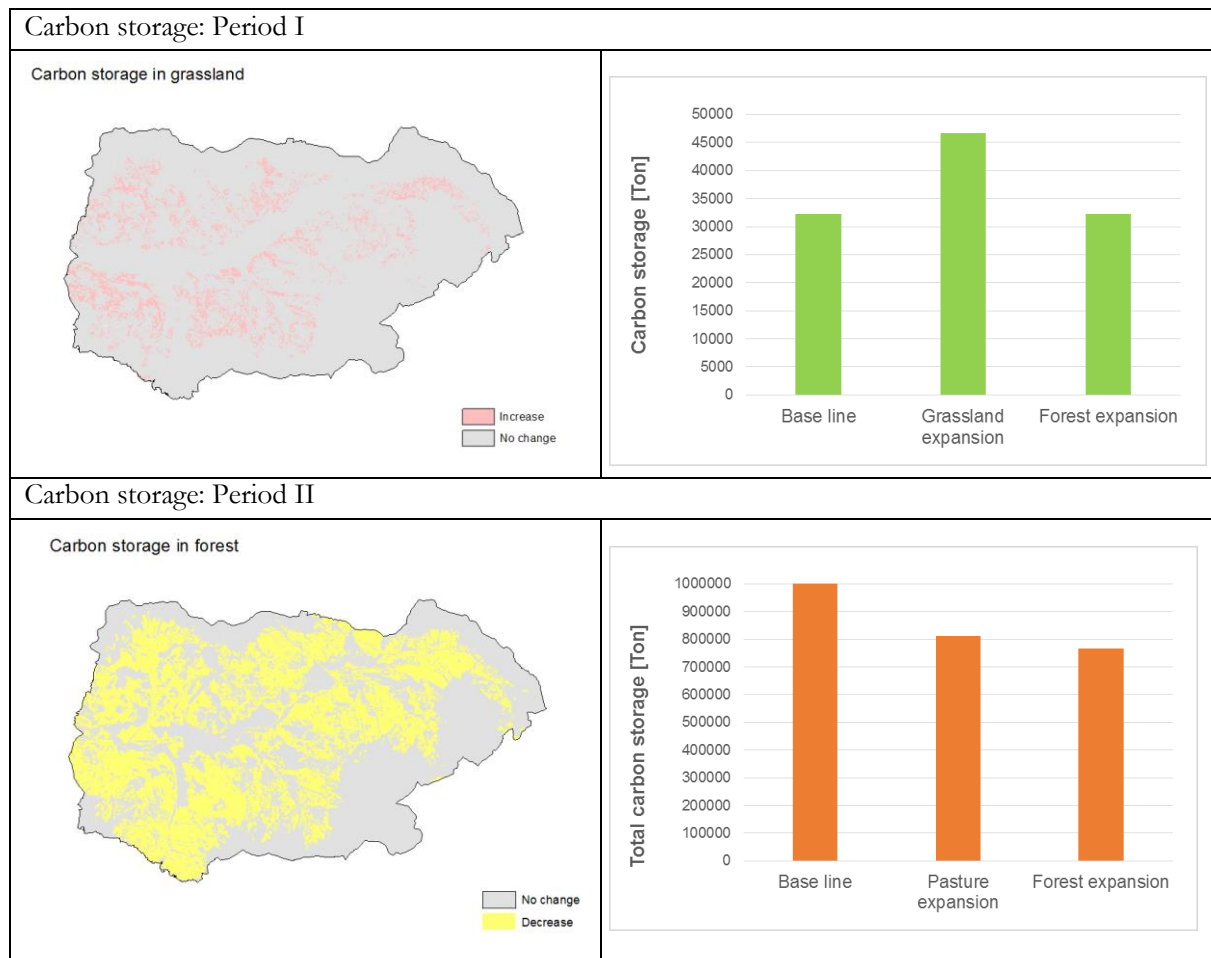


Figure 21: Carbon storage of forest and grassland in Scenarios A and B

During the second period that included the expansion of pasture and forest (Coniferous forest) in the study area, there is a decrease of 20% and 24% respectively in comparison of the initial carbon storage, this is due to the fact that both scenarios converted Coniferous forest cover to another type of cover (grassland or pasture and young coniferous forest < 20 years) with less capacity to store carbon.

In fact the carbon storage of the expansion of coniferous mixed forest cover is 25% less than the forest cover of the no intervention scenario (Figure 21 –Carbon storage in forest- Scenario B map). Aspect that reveals the need to consider a larger time span (more than 20 years) for forest interventions to have a

favourable effect in carbon storage or increase the area of forest interventions with native tree species that can have a faster growth in biomass.

Risk reduction

The result obtained from the landslides susceptibility assessment where described in the previous paragraphs. To target possible high consequence locations for detailed risk assessments, the Potential Damage Index (PDI) framework (Puissant et al., 2013) was used to locate the most sensitive areas, this index allows the estimation of physical injury, structural and functional damage and socio-economic effects of EaR. Taking into account that winter tourism as the main economic activity of the region, the values of Damage winter index were consider. Additionally, this framework considers land cover as an element at risk, therefore a PDI maps for scenario A (grassland interventions) and B (forest interventions) were generated. Figure 22 presents the PDI map produced for winter season (no intervention), from the map we can observe that buildings and roads are the elements at risk with a higher vulnerability and arable land has a very low PDI.

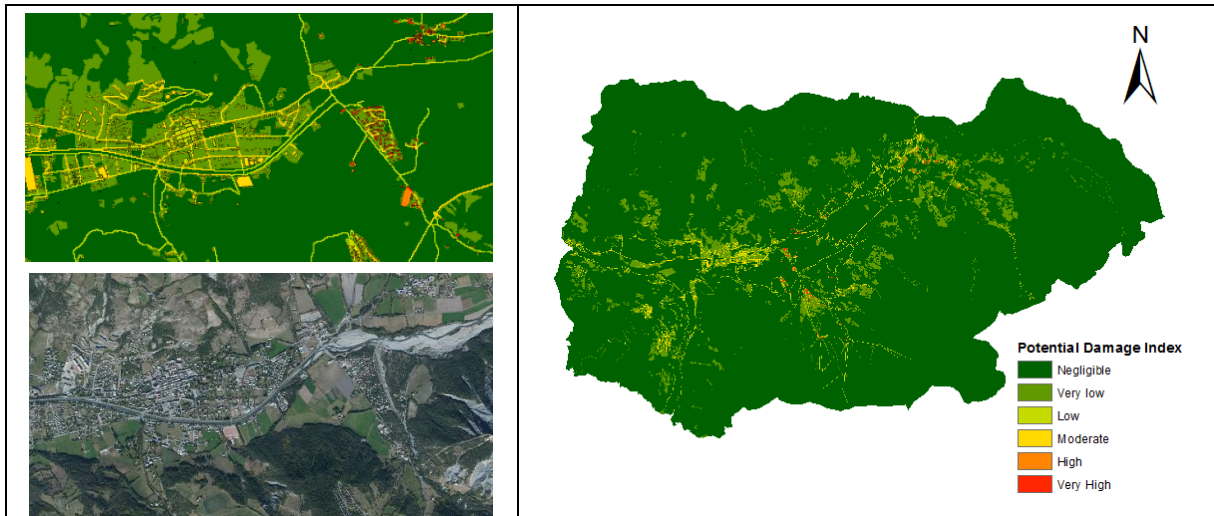


Figure 22: Potential Damage Index map of the no intervention scenario.

In the case of the landslides risk reduction, the risk matrix shows that 44% of the study area located in high landslides susceptibility but with a negligible potential damage, meaning that the effect of the ecosystem-based measure will not make a mayor difference for risk reduction.

Landslide susceptibility (Hazard)	Potential damage (vulnerability)											
	Negligible		Very low		Low		Moderate		High		Very High	
	Km ²	%	Km ²	%	Km ²	%	Km ²	%	Km ²	%	Km ²	%
Null	9.83	4.48	2.68	1.22	0.61	0.28	0.54	0.25	0.04	0.02	0.06	0.03
Low	29.56	13.47	0.66	0.30	0.12	0.05	0.11	0.05	0.01	0	0.02	0.01
Moderate	66.12	30.14	10.04	4.58	0.38	0.17	0.33	0.15	0.01	0	0.01	0.01
High	95.90	43.71	1.06	0.48	0.89	0.41	0.26	0.12	0.04	0.02	0.09	0.04

In terms of landslides risk, Figure 23 illustrate the changes in the risk classes for the ecosystem-based measures where the high risk areas are located mainly in areas close to roads, building and pasture land.

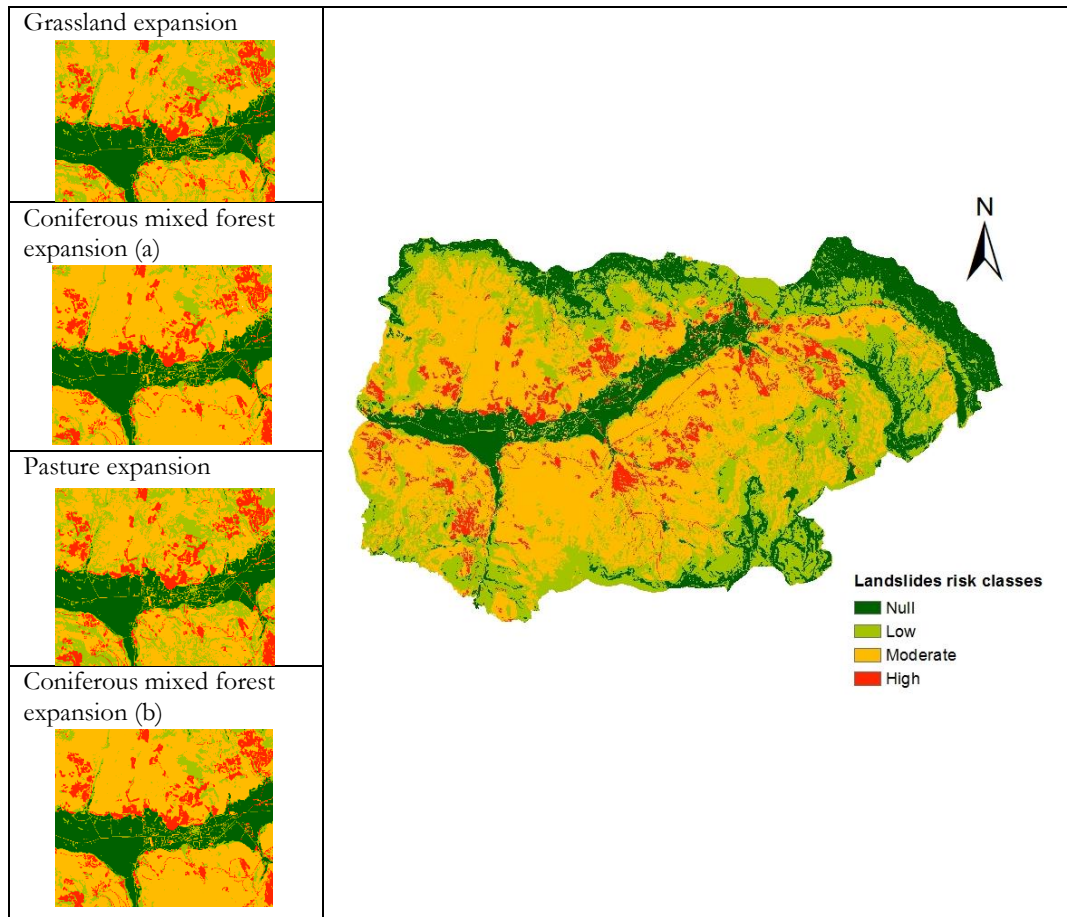


Figure 23: Effect of ecosystem-based measures in risk

During the first period of the implementation of the ecosystem-based measures, in Figure 24 we can observe a reduction of 20% from moderate to low risk class for scenario A (grassland expansion) and for scenario B the risk remain the same as the base line scenario.

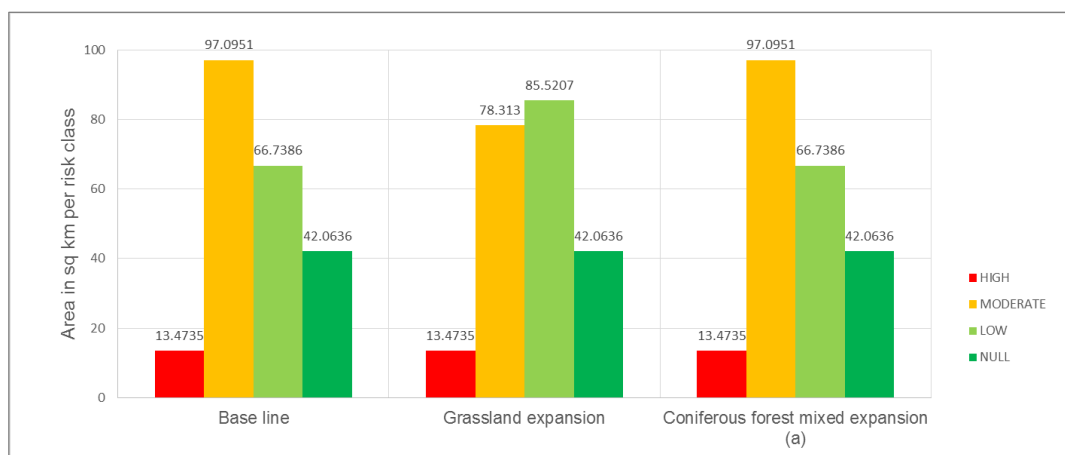


Figure 24: Comparison of the effect of ecosystem-based measures in risk - Period 1

For the second period (Figure 25), the pasture expansion shows a reduction of 22% of the area that change the risk from moderate to low. For forest expansion the values obtained for scenario B show a reduction less than 1% in moderate, low and null risk classes.

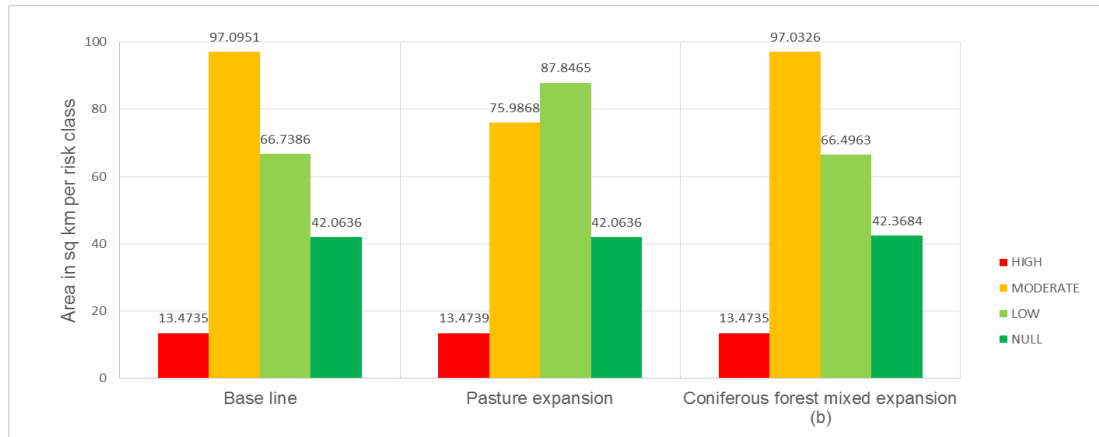


Figure 25: Comparison of the effect of ecosystem-based measures in risk - Period 2

4.3.2. Overall performance for both ecosystem-based measures over time

Even though quantified services give a direct view on the relation between the no intervention and ecosystem-based scenarios, for decision making purposes it is important to translate the benefit in to percentages that can allow to see the overall performance, like is shown in Figure 26 that summarize the overall performance of the ecosystem-based measures implemented.

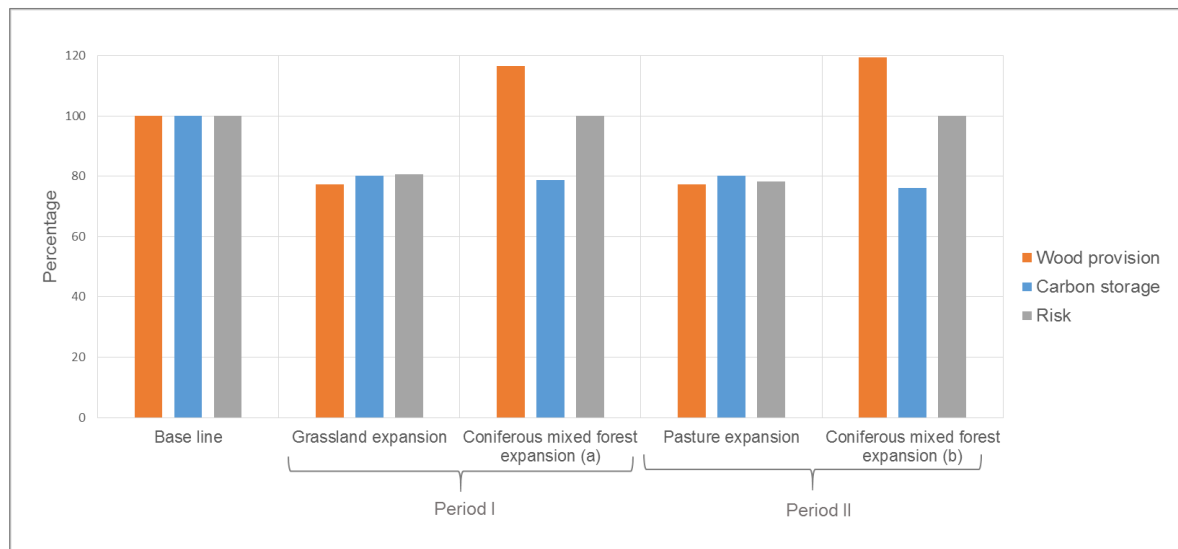


Figure 26: Overall performance of the ecosystem-based measure and the supply of ecosystem services for the study area, for period I and II.

From the figure we can clearly see that scenario B provides approximately 20% more of raw material, than scenario B. The opposite happens with the total carbon storage where all ecosystem based measure show a decrease of 20 % in carbon storage.

In terms of risk, Figure 26 only presents the effect the ecosystem-based measures in the moderate risk class (where the changes were identified); showing that only scenario A can have a real effect in risk reduction.

5. DISCUSSION

5.1. Shallow landslides susceptibility assessment

This study aimed at developing a GIS based methodological framework to assess the effectiveness of ecosystem-based measures over time in reducing shallow landslide susceptibility.

In this context, a landslide susceptibility assessment was used to determine two main components of the framework. Firstly, the conditioning factors and their relation with the occurrence of landslides based on a statistical approach, especially with the land cover layer which is the main factor that can be changed and simulate its effect on reducing shallow landslides susceptibility. Secondly, the location and the extent of the areas susceptible to landslides, to know where are the areas where the landslides reduction measures needed to be taken.

Conditioning factors

In this thesis the conditioning factors (slope, geotype and land cover) were identified using the weight of evidence model and were used as independent variables for the elaboration of the landslide susceptibility maps. According to the literature (Bonham-Carter, 1994), there should be a strong relation between failure mechanism and factors to include in the model and also be independent among each other. In this research the selection of these factors was made according to their physical meaning, availability of data and the conditional independent test.

Modelling

The contrast values obtained from the weight of evidence method show that the classes favouring landslides occurrence are slope (classes from 10 to 30°) and land cover (coniferous and broad leaved forest cover). Concluding that shallow landslides are largely determined by land cover and slope factors. However, it is important to clarify that the weights assigned to each class within a conditional factor map in the WoE model is determined by the number of landslide pixels counted in each class and the difference in the number of pixels between the classes. This aspect can derived in an overestimation of the weights of contrast values in cases of the factor class and the number of non-landslides pixels in these classes are smaller (H. Hussin et al., 2015) like is the case of Broad leaved forest and marine outcrops.

In the context of the methodological framework, the selection of the optimal model is based on the model that contains sufficient complexity to explain the landslides phenomena. Therefore, model B that considers only 3 factors: slope, geotype and land cover was chosen as more accurate than others to prepare the final landslides susceptibility map

A clear advantage of the use of the weight of evidence method is the avoidance of subjectivity in weighting the factor classes and it also avoids the use of inter-correlated landslide factors (Regmi et al., 2010).

Additionally, the results show that 20% (sample size testing) of the landslide inventory can be sufficient to train the model and produce adequate success rates, there is only 2% of increase in success rates associated with the increase in pixels (50%) representing the landslide scarp polygons. This results correspond well

with recent previous studies that used scarp polygon to predict shallow landslide (Hussin et al., 2015; Petschko, Brenning, Bell, Goetz, & Glade, 2014). Therefore, there is no difference in the overall model performance and prediction between the sampling strategies, which indicates the model seems robust to predict landslide location.

One of the limitations of the landslide susceptibility assessment is the accuracy and unknown quality of the input data. First, the use of the landslides inventory of the year 2007 to train and validate the model can show limited correspondence between future landslides events and the final output. In general statistical models are sensitive to the thematic factors used; therefore a much more emphasis should be given on the analysis of appropriate input data, principally if the purpose of the study includes the temporal aspect, is recommended to match the occurrence of landslides with the year of the land cover layers. (Thiery et al., 2007). Second, the scale of the thematic maps in comparison with the grid-cell resolution for susceptibility mapping using small scale maps (1:1000,000 to 2:200,000) causes higher geographic inaccuracies, where a few millimetre on the factor maps can translate into error of several grid cells (Hussin et al., 2015).

5.2. Effect of ecosystem-based measures on reducing landslides susceptibility over time

The major challenges in the assessment of the effect of ecosystem-based measures in reducing landslides susceptibility were the: simulation of ecosystem-based measures (location and extent) in the land cover layer and the incorporation of time aspect.

Ecosystem-based measures

For the location of the ecosystem-based measures, three spatial criteria were implemented; selecting the areas with high susceptibility to landslides (where the measures are needed based on the spatial probability of occurrence), including the guidelines of the local French authorities which define slopes between 20-30 degrees require mitigation works and areas within a distance of 500 m to elements at risk (considering the vulnerability of roads to landslides) and the selection of the type of ecosystem-based measure (land cover class) to be incorporate was in line with the current type of land cover reduction management performed by the local authorities that has been implemented since the year 1887. This is important when carrying out a computer based study to obtain consistent results that represent the real effect of ecosystem based measure, one has to be aware of the local reglamentation and practices implemented in the area.

Time aspect

When developing the ecosystem-based measures, two main changes (forest and grassland expansion) were aimed to be assessed over time, since the ecosystem-based measures were implemented in the study area, thus to incorporate the temporal component in the landslides susceptibility assessment, temporal land cover layers matching with the date of landslides occurrence were required and were not available.

In the context of the methodological framework, the temporal scale can be defined by stakeholders. However, due to the data availability constrains in this research it was assumed that land cover changes will only occur in the areas where ecosystem-based interventions are needed while leaving the other land cover classes unchanged and assuming a successive type of ecosystem-based management in the area. This approach is used by InVEST (Integrated Valuation of Ecosystem Services and Trade-offs tool developed

by Natural Capital Project) that link the land use and land cover (LULC) patterns and land-management scenarios to predict the production of ecosystem-services outputs. The inclusion of both land use and land cover means that we can consider management choices that affect the type of land cover (Tallis & Polasky, 2009).

Model assumptions

For the grassland expansion the major changes occur in the high susceptibility class, where there is a decrease of susceptibility of 22% from high to moderate susceptibility. For the forest expansion, few changes (from moderate to low susceptibility class) were observed comparing the susceptibility maps with the base line, this can be explained by the criteria of location previously applied that define the extent of area projected to change (less than 1.3% of the whole area). Therefore, planted grass shows better results on reduction landslides susceptibility.

This results should be carefully consider, in view of that forest's ability to protect an area from landslides depends on its position in relation to the hazard, and in the majority of the cases landslides forest control is not implemented in the departure zone of transit and stopping zone (Clouet & Berger, 2010). Additionally is important to consider that forest is a dynamic system, which cannot be maintained in a particular state over a long period of time (Brang, 2001) the stand structure is constantly changing, which likewise influences and continuously changes the protective effect of a forest (Wehrli, 2005).

5.3. Overall performance of different ecosystem-based measures over time

Three indicators were used to quantify the overall performance of the ecosystem-based measures over time, two of this indicators are related with the supply of ecosystem services (wood provision and carbon storage) and one on the risk reduction (that integrate the landslides susceptibility zonation and Potential Damage Index).

Provision of raw material

This indicator is related to data in a large scale of forest production (France) that in some cases cannot be available in a local scale (like is the case of the Barcelonnette basin). Based on the results, the indicator can be useful to show a favourable effect in the overall performance for ecosystem-based measures that involve the plantation of forest considering a sustainable management over time and be linked with potential economic benefits.

Carbon storage

This research applied the simplest level for establishing relationship between land cover types and carbon stocks (Crossman et al., 2013) by using the values provided by IPCC (2006), to approximate the effect of the ecosystem-based measure in the total carbon storage. The analysis was restricted to aboveground carbon and showed a reduction of approximately 22% of total carbon storage with the implementation of all measures.

Landslide risk reduction

The landslides risk reduction was obtained using the landslides susceptibility model with the different land cover scenario maps in order to obtain different susceptibility set ups that were combined with their corresponding PDI maps. This is one of the advantages of the PDI methodology, which considers the effect of landslides (hazard) on land cover maps (as a direct structural/functional impact), therefore the changes in the land cover scenarios were consider as well. Another, advantage is using a composite index, is that the information is easily accessible to the general public, technicians, local and regional planner, insurance companies, government agencies another potential users (Puissant et al., 2006). Results showed that grassland and pasture interventions are able to reduce a 20% of the risk (from moderate to low) in the study area.

However, the data used for calculating the indictors was obtained from literature reviews and national statistics, these data are often irregular and in some cases base on one-off or ad hoc studies, rather than ongoing monitoring. Therefore improving the data collected at a local scale could be essential to develop of a robust set of ES indicators (UNEP-WCMC, 2011).

Overall performance

The ecosystem- based measures scenario which rank the best in terms of ES supply and risk reduction is the grassland and pasture scenario. In the context of the methodological framework, to get insight in the landslides reduction performance over time, these results need to be complemented with the proper identification and selection of plant species for slope stabilization based on their ability to establish and grow in the area. According to Stokes et al. (2014) the combination of species should be encouraged, because in most cases slope sustainability can only be obtained through the establishment of successional processes that can be a long-term solution for restoration and protection.

The relevance of including ES indicators enhance the understanding of the overall ecosystem functioning and avoids to overlook the total benefits of ecosystem-based measures. In addition, these type of measures may serve as habitats or migration corridors for certain species that bring economic benefits, such as pollination of crops or wildlife ecotourism and other recreational activities.

The combination of these three indicators is substantial for the methodological framework given that the same layer (land cover) can be used as a conditional factor that can reduce the spatial probability of the occurrence of landslide, as a potential vulnerable resource that needs to be protected (because of their intrinsic protective value) and a source of potential benefits, showing the multiple functions of the ecosystem-based measures.

The ecosystem-based measures are perhaps the most overlooked component in disaster risk reduction and development planning, they are still perceived by many as having conservation value only its role in terms of providing hazard protection, livelihood recovery and sustainability and resilient development is often ignored(Renaud et al., 2013). The result of this research provides explorative steps to measure the overall performance and represent a tool to quantify the multiple benefits that these type of measures can provide to an area. Additionally, with this approach seasonal vegetation cover changes in addition to socio -economic changes can be taken into account.

Accuracy/certainty

The methodological framework does not consider other potential future land changes, such as urban or arable land cover changes that can influence the occurrence to landslides and impact the overall performance.

Methodological framework replicability & applicability

To ensure transferability of the framework to other study areas spatial data availability can be one of the major constraints, especially in regions where ecosystem services (vegetation growth, carbon storage of specific forest species) and socio-economic data (elements at risk) is lacking or incomplete. Although the proposed methodological framework shows the best use of available data and the inherent characteristics of a study area, by using spatial biophysical, socioeconomic and land cover data that is already available, generating more insights without the need to gather new data.

Policy makers can use the information generated to design spatial policies and evaluate (ex-ante) the effect of the ecosystem-based-measures and their capacity to provide benefits. Making the assessment of the ecosystem-based measures spatial explicit while most other quantification methods lack a spatial component. By linking service supply of ecosystems with explicit spatial criteria, it is possible to identify hot spots that show the total performance over time of reforestation and grass-based interventions on reducing landslides risk. Additionally, the selection and quantification of spatial indicators to show the benefits can give insight into important components of the type of management of the measures.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1. Conclusion

This thesis explored a GIS based approach to assess the effectiveness of ecosystem-based measures over time in reducing shallow landslides susceptibility. To accomplish this, the weight of evidence model was useful to assess landslides susceptibility under changing conditions, in combination with spatial explicit indicators to quantify the overall performance.

The slope and land cover layers were identified as conditioning factor of shallow landslides in the study area, using the weight of evidence model and were used as independent variables for the elaboration of the landslide susceptibility maps.

In the methodological framework temporal data constrains was overcome by developing ecosystem-based measure scenarios that linked the land cover patterns and ecosystem-based management to predict the supply of ecosystem-services. From the assessment of the effect of ecosystem-based measures in reducing landslides susceptibility over time, grass interventions showed better results on reduction landslides susceptibility.

The total performance of ecosystem-based measures was expressed by landslides risk reduction and other ecosystem services provided such as wood provision and carbon storage. The ecosystem- based measures scenario which rank the best in terms of ES supply and risk reduction is the grassland and pasture scenario.

6.2. Recommendation

- Future research should focus on explore a quantitative and spatially explicit approach that include the interaction of ecosystem-based measures with each other and assess their potential economic benefit.
- Much still needs to be learned about how ecosystem-based measures can integrate with engineered solutions and addresses the needs of local cultures and ecosystems, thorough the involvement of stakeholders.

LIST OF REFERENCES

- Alcántara-Ayala, I., Esteban-Chávez, O., & Parrot, J. F. (2006). Landsliding related to land-cover change: A diachronic analysis of hillslope instability distribution in the Sierra Norte, Puebla, Mexico. *CATENA*, 65(2), 152–165. doi:10.1016/j.catena.2005.11.006
- Armas, L., Stroia, F., & Giurgea, L. (2013). Statistic Versus Deterministic Method for Landslide Susceptibility Mapping. In C. Margottini, P. Canuti, & K. Sassa (Eds.), *Landslide Science and Practice* (Vol. 2, pp. 383–388). Berlin, Heidelberg: Springer Berlin Heidelberg. doi:10.1007/978-3-642-31310-3
- Australian Geomechanics Society. (2000). *Landslide Risk Management Concepts and Guidelines*. Australian Geomechanics Society Sub-Committee on landslide risk management. Retrieved from <http://australiangeomechanics.org/admin/wp-content/uploads/2010/11/LRM2000-Concepts.pdf>
- Beguería, S. (2006). Validation and evaluation of predictive models in hazard assessment and risk management. *Natural Hazards*, 37(3), 315–329. doi:10.1007/s11069-005-5182-6
- Berger, F., & Rey, F. (2004). Mountain protection forests against natural hazards and risks: New french developments by integrating forests in risk zoning. *Natural Hazards*, 33(3), 395–404. doi:10.1023/B:NHAZ.0000048468.67886.e5
- Bonham-Carter, G. F. (1994). *Geographic Information Systems for Geoscientists*. *Geographic Information Systems for Geoscientists*. doi:10.1016/B978-0-08-041867-4.50013-8
- Brang, P. (2001). Resistance and elasticity: Promising concepts for the management of protection forests in the European Alps. *Forest Ecology and Management*, 145(1-2), 107–119. doi:10.1016/S0378-1127(00)00578-8
- Clerici, A., Perego, S., Tellini, C., & Vescovi, P. (2002). A procedure for landslide susceptibility zonation by the conditional analysis method. *Geomorphology*, 48(4), 349–364. doi:10.1016/S0169-555X(02)00079-X
- Clouet, N., & Berger, F. (2010). New Gis Developments in Mountain Protection Forests. In *Proceedings of the International Symposium Interpraevent 2010, 26-30 April* (Vol. 33, pp. 382–390). Taipei, Taiwan. Retrieved from http://www.interpraevent.at/palm-cms/upload_files/Publikationen/Tagungsbeitraege/2010__382.pdf
- Crossman, N. D., Burkhard, B., Nedkov, S., Willemen, L., Petz, K., Palomo, I., ... Maes, J. (2013). A blueprint for mapping and modelling ecosystem services. *Ecosystem Services*, 4, 4–14. doi:10.1016/j.ecoser.2013.02.001
- Crozier, M. J., & Glade, T. (2005). Landslide Hazard and Risk: Issues, Concepts and Approach. In T. Glade, M. Anderson, & M. Crozier (Eds.), *Landslide Hazard and Risk* (pp. 1–40). Chichester, West Sussex, England: John Wiley & Sons, Ltd. doi:10.1002/9780470012659.ch1
- Demontzey, P. (1882). *Traité pratique du reboisement et du gazonnement des montagnes*. (J. Rothschild, Ed.) *Zhurnal Eksperimental'noi i Teoreticheskoi Fiziki* (Second Edi.). Paris. Retrieved from <http://gallica.bnf.fr/ark:/12148/bpt6k6130912k/f46.item.r=gazonneme.zoom>
- Dolidon, N., Hofer, T., Jansky, L., & Sidle, R. (2009). Watershed and Forest Management for Landslide Risk Reduction. In K. Sassa & P. Canuti (Eds.), *Landslides – Disaster Risk Reduction*. Berlin, Heidelberg: Springer Berlin Heidelberg. doi:10.1007/978-3-540-69970-5
- Dominati, E., Patterson, M., & Mackay, A. (2010). A framework for classifying and quantifying the natural capital and ecosystem services of soils. *Ecological Economics*, 69(9), 1858–1868. doi:10.1016/j.ecolecon.2010.05.002
- Dorren, L. K. A., Berger, F., Imeson, A. C., Maier, B., & Rey, F. (2004). Integrity, stability and management of protection forests in the European Alps. *Forest Ecology and Management*, 195(1-2), 165–176. doi:10.1016/j.foreco.2004.02.057
- Estrella, M., & Saalismaa, N. (2012). The Role of Ecosystems Management for Disaster Risk Reduction. In

- A. K. Gupta & S. S. Nair (Eds.), *Ecosystem approach to Disaster Risk Reduction* (p. 202). New Delhi: National Institute of Disaster Management. Retrieved from https://www.gdnonline.org/resources/nidm_ecosystem_approach.pdf
- Eurostat. (2009). *Forestry statistics. Office of the European Union* (Vol. 9). Luxembourg. doi:10.1093/jicru/ndp017
- Fell, R., Corominas, J., Bonnard, C., Cascini, L., Leroi, E., & Savage, W. Z. (2008). Guidelines for landslide susceptibility, hazard and risk zoning for land use planning. *Engineering Geology*, 102(3-4), 85–98. doi:10.1016/j.enggeo.2008.03.022
- Flageollet, J.-C., Maquaire, O., Martin, B., & Weber, D. (1999). Landslides and climatic conditions in the Barcelonnette and Vars basins (Southern French Alps, France). *Geomorphology*, 30(1-2), 65–78. doi:10.1016/S0169-555X(99)00045-8
- Georgi, N. J., & Stathakopoulos, J. E. (2016). Bioengineering techniques for soil erosion protection and slope stabilization. *Landscape*, (Figure 1).
- Glade, T. (2002). Ranging scales in spatial landslide hazard and risk analysis. *Third International Conference on Risk Analysis*, 19-21(June 2002), 719–729.
- Glade, T., & Crozier, M. J. (2005). The Nature of Landslide Hazard Impact. In T. Glade, M. Anderson, & M. Crozier (Eds.), *Landslide Hazard and Risk* (pp. 43–74). Chichester, West Sussex, England: John Wiley & Sons, Ltd. Retrieved from <http://www.geomorphology.uni-bonn.de/publications>
- Guzzetti, F., Reichenbach, P., Cardinali, M., Galli, M., & Ardizzone, F. (2005). Probabilistic landslide hazard assessment at the basin scale. *Geomorphology*, 72(1-4), 272–299. doi:10.1016/j.geomorph.2005.06.002
- Hussin, H. Y. (2011). *Probabilistic Run-out Modeling of a Debris Flow in Barcelonnette, France. MSc Thesis*. University of Twente. Retrieved from http://www.itc.nl/library/papers_2011/msc/aes/hussin.pdf
- Hussin, H., Zumpano, V., Reichenbach, P., Sterlacchini, S., Micu, M., van Westen, C., & Bălteanu, D. (2015). Different landslide sampling strategies in a grid-based bi-variate statistical susceptibility model. *Geomorphology*, 253, 508–523. doi:10.1016/j.geomorph.2015.10.030
- International Federation of Red Cross and Red Crescent Societies. (2002). *World Disaster Report 2002 - Focus on reducing risk*. Retrieved from <https://www.ifrc.org/PageFiles/89755/2002/32600-WDR2002.pdf>
- IPCC. (2006). 2006 IPCC Guidelines for National Greenhouse Gas Inventories, prepared by National Greenhouse Gas Inventories Programme. In H. S. Eggleston, L. Buendia, K. Miwa, T. Ngara, & K. Tanabe (Eds.), (Vol. 4, p. 49). IGES, Japan. doi:http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/2_Volume2/V2_3_Ch3_Mobile_Combustion.pdf
- Liébault, F., & Taillefumier, F. (2000). L'évolution contemporaine de la bande active des principaux affluents de la Drôme, de l'Eygues et du Roubion (Préalpes du Sud, France). / The contemporary development of the active tract of the main tributaries of the Drôme, the Eygues and Roubion, in the. *Géocarrefour*, 75(4), 327–336. doi:10.3406/geoca.2000.2484
- Lopez Saez, J. (2011). *Reconstruction de l'activité des glissements de terrain au moyen d'une approche dendrogeomorphologique (Moyenne vallée de l'Ubaye, Alpes de Haute Provence)*. Université de Grenoble. Retrieved from <https://tel.archives-ouvertes.fr/tel-00716338>
- Maes, J., Egoh, B., Willems, L., Lique, C., Vihervaara, P., Schägner, J. P., ... Bidoglio, G. (2012). Mapping ecosystem services for policy support and decision making in the European Union. *Ecosystem Services*, 1(1), 31–39. doi:10.1016/j.ecoser.2012.06.004
- Malek, Ž., Boerboom, L., & Glade, T. (2015). Future Forest Cover Change Scenarios with Implications for Landslide Risk: An Example from Buzău Subcarpathians, Romania. *Environmental Management*. doi:10.1007/s00267-015-0577-y
- Malet, J.-P., Laigle, D., Remaitre, A., & Maquaire, O. (2005). Triggering conditions and mobility of debris flows associated to complex earthflows. *Geomorphology*, 66(1-4), 215–235.

doi:10.1016/j.geomorph.2004.09.014

- Martínez-Harms, M. J., & Balvanera, P. (2012). Methods for mapping ecosystem service supply: a review. *International Journal of Biodiversity Science, Ecosystem Services & Management*, 8(1-2), 17–25. doi:10.1080/21513732.2012.663792
- Millennium Ecosystem Assessment. (2005). *Ecosystem and Human Well-being: Synthesis*. Washington, DC. Retrieved from <http://www.unep.org/maweb/documents/document.356.aspx.pdf>
- Munang, R., Thiaw, I., Alverson, K., Liu, J., & Han, Z. (2013). The role of ecosystem services in climate change adaptation and disaster risk reduction. *Current Opinion in Environmental Sustainability*, 5(1), 47–52. doi:10.1016/j.cosust.2013.02.002
- Nguyen, T.-N., & Liu, C.-C. (2014). Combining bivariate and multivariate statistical analyses to assess landslide susceptibility in the Chen-Yu-Lan watershed, Nantou, Taiwan. *Sustainable Environment Research*, 24(4), 257–271.
- Papathoma-Koehle, M., & Glade, T. (2013). The role of vegetation cover change in landslide hazard and risk. In F. Renaud, K. Sudmeier-Rieux, & M. Estrella (Eds.), *The Role of Ecosystems in Disaster Risk Reduction* (pp. 293–319). United Nations University Press. Retrieved from <http://books.google.com/books?id=9mTRjKmN1LwC>
- Peduzzi, P. (2010). Landslides and vegetation cover in the 2005 North Pakistan earthquake: a GIS and statistical quantitative approach. *Natural Hazards and Earth System Science*. doi:10.5194/nhess-10-623-2010
- Petschko, H., Brenning, A., Bell, R., Goetz, J., & Glade, T. (2014). Assessing the quality of landslide susceptibility maps - case study Lower Austria. *Natural Hazards and Earth System Sciences Discussions*, 1(2), 1001–1050. doi:10.5194/nhessd-1-1001-2013
- Phillips, C. J., Rey, F., Marden, M., & Liébault, F. (2013). Revegetation of steep lands in France and New Zealand: Geomorphic and policy responses. *New Zealand Journal of Forestry Science*, 43, 1–16. doi:10.1186/1179-5395-43-14
- Puissant, A., Malet, J., & Maquaire, O. (2006). Mapping landslide consequences in mountain areas: a tentative approach with a semi-quantitative procedure. *Sageo*, (ii), 16.
- Puissant, A., Van Den Eeckhaut, M., Malet, J. P., & Maquaire, O. (2013). Landslide consequence analysis: a region-scale indicator-based methodology. *Landslides*, 1(August 2013), 1–16. doi:10.1007/s10346-013-0429-x
- Quadt, V., van der Maaten-Theunissen, M., & Krumm, F. (2013). *Integration of Nature Protection in Austrian Forest Policy. INTEGRATE Country Report for Austria. INTEGRATE Country Report. EFICENT-OEF, Freiburg.* Freiburg. Retrieved from <http://www.eficent.efi.int/files/attachments/eficent/projects/austria.pdf>
- Regmi, N. R., Giardino, J. R., & Vitek, J. D. (2010). Modeling susceptibility to landslides using the weight of evidence approach: Western Colorado, USA. *Geomorphology*, 115(1-2), 172–187. doi:10.1016/j.geomorph.2009.10.002
- Remaître, A., & Malet, J.-P. (2010). The effectiveness of torrent check dams to control channel instability: example of debris flow events in clay shales. In *Check Dams, Morphological Adjustments and Erosion Control in Torrential Streams* (pp. pp. 211–237).
- Renaud, F. G., Sudmeier-Rieux, K., & Estrella, M. (2013). The relevance of ecosystems for disaster risk reduction. In M. Renaud, F.G., Sudmeier-Rieux, K., Estrella (Ed.), *The role of ecosystems in disaster risk reduction* (p. 440). Tokyo: UNU-Press. Retrieved from <https://collections.unu.edu/view/UNU:1995#.Vdc4dZx7dVs.mendeley>
- SafeLand Seventh Framework Programme, & Faculty of Geo-information Science and Earth Observation of the University of Twente. (2012). Use of weights of evidence modeling for landslide susceptibility

- mapping: Alvaro area, Basilicata, Italy. In *SafeLand- Living with landslide risk in Europe: Assessment, effect of global change, and risk management strategies* (p. 133). Retrieved from <ftp://ftp.itc.nl/pub/westen/safeland/>
- Soeters, R., & Van Westen, C. J. (1996). Slope instability, recognition, analysis, and zonation. In L. R. Turner, A K Schuster (Ed.), *Landslides: Investigation and mitigation* (Transporta., pp. 129–177). Washington, D.C: National Research Council.
- Stokes, A., Douglas, G. B., Fourcaud, T., Giadrossich, F., Gillies, C., Hubble, T., ... Walker, L. R. (2014). Ecological mitigation of hillslope instability: Ten key issues facing researchers and practitioners. *Plant and Soil*, 377(1-2), 1–23. doi:10.1007/s11104-014-2044-6
- Tallis, H., & Polasky, S. (2009). Mapping and valuing ecosystem services as an approach for conservation and natural-resource management. *Annals of the New York Academy of Sciences*, 1162, 265–283. doi:10.1111/j.1749-6632.2009.04152.x
- Thiery, Y., Malet, J.-P., Sterlacchini, S., Puissant, A., & Maquaire, O. (2007). Landslide susceptibility assessment by bivariate methods at large scales: Application to a complex mountainous environment. *Geomorphology*, 92(1-2), 38–59. doi:10.1016/j.geomorph.2007.02.020
- Thiery, Y., Sterlacchini, S., Malet, J., Puissant, A., Remaître, A., & Maquaire, O. (2004). Strategy to Reduce Subjectivity in Landslide Susceptibility Zonation by GIS in Complex Mountainous Environments. In *7th AGILE Conference on Geographic Information Science* 29 April-1 May 2004, Parallel Session 7.3- "Decision Support Systems / Risk Management II" (pp. 623–634). Heraklion, Greece. Retrieved from <https://hal.archives-ouvertes.fr/hal-00276831>
- UNEP-WCMC. (2011). *Developing ecosystem service indicators: Experiences and lessons learned from sub-global assessment and other initiatives*. Canada. Retrieved from http://www.seachangecop.org/sites/default/files/documents/2011_06_CBD_-_Developing_Ecosystem_Service_Indicators.pdf
- Van Westen, C. J., Rengers, N., & Soeters, R. (2003). Use of geomorphological information in indirect landslide susceptibility assessment. *Natural Hazards*, 30(3), 399–419. doi:10.1023/B:NHAZ.0000007097.42735.9e
- Wainwright, J., & Mulligan, M. (2004). *Environmental Modelling*. (J. Wainwright & M. Mulligan, Eds.). Chichester, UK: John Wiley & Sons, Ltd. doi:10.1002/9781118351475
- Wehrli, A. R. (2005). *Mountain forest dynamics and their impacts on the long-term protective effect against rockfall - A modelling approach*. Phd thesis. University of Zurich. Retrieved from <http://e-collection.library.ethz.ch/eserv/eth:28456/eth-28456-02.pdf>